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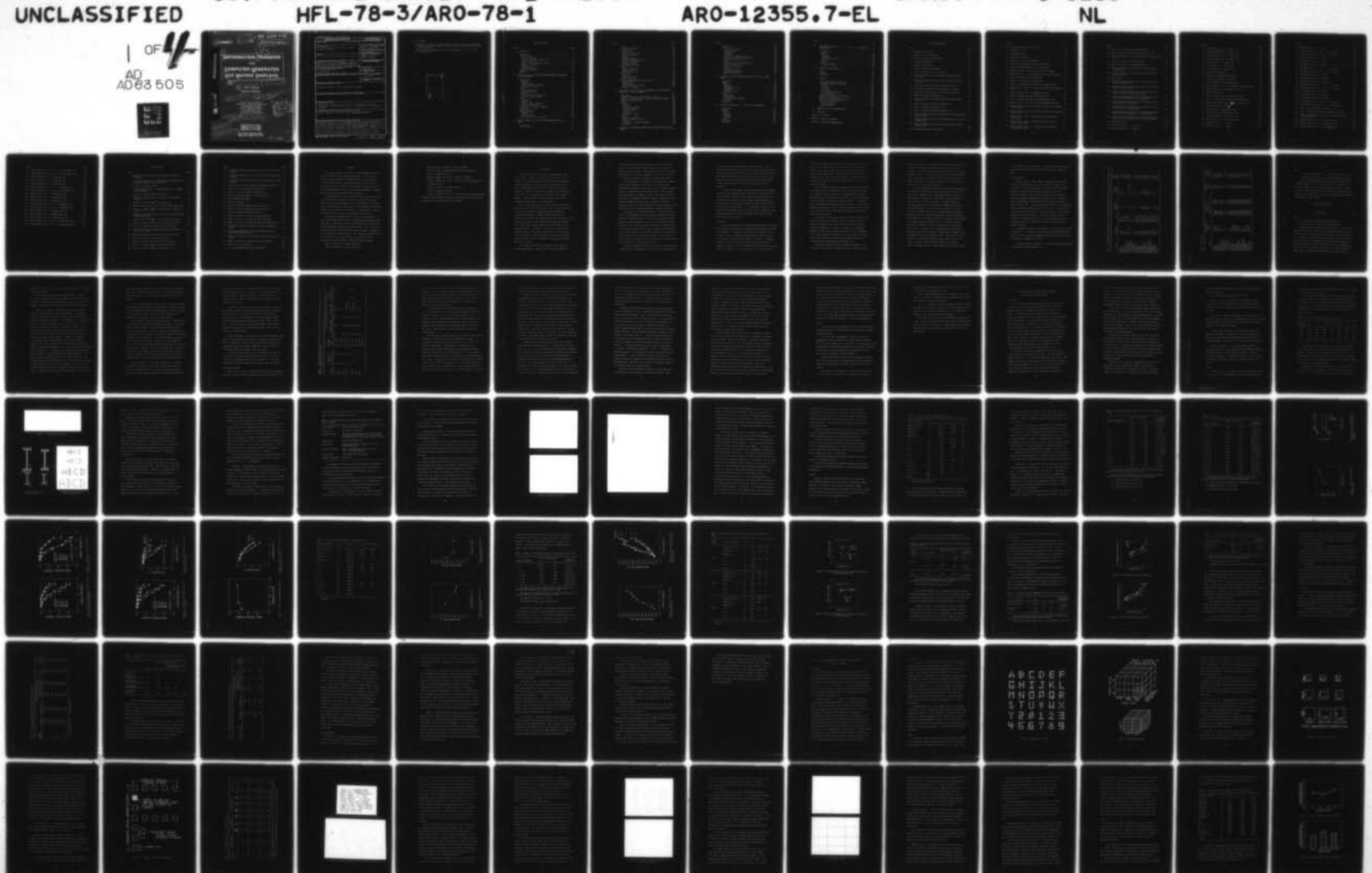

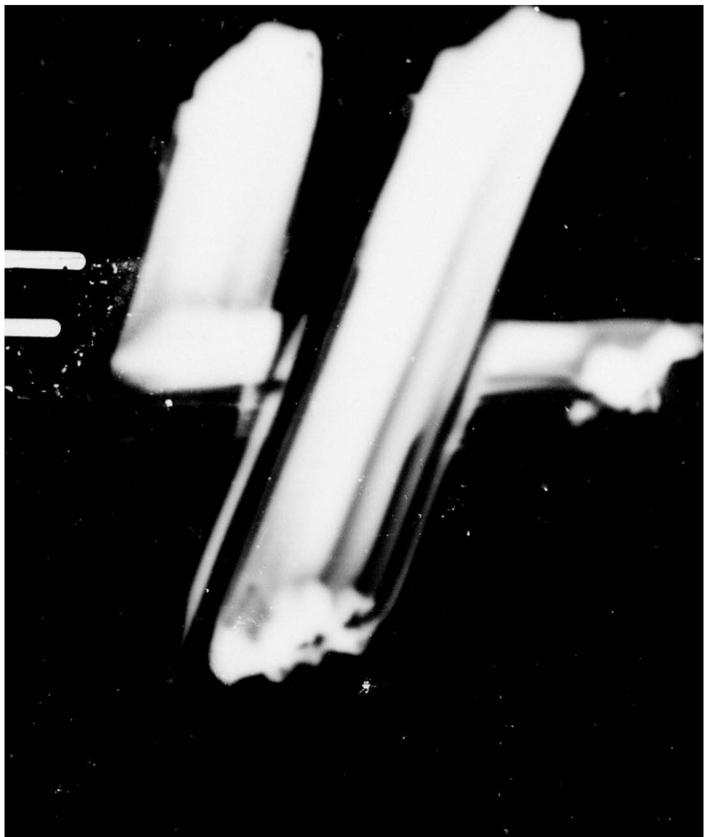

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This report summarizes a research program which has investigated the effects of numerous design parameters of alphanumeric dot-matrix displays upon operator performance. Among the parameters investigated experimentally are dot size, dot shape, dot contrast (or modulation), dot spacing, matrix size, character size, word context, ambient illuminance, character (dot) luminance, and character font.

Operator performance in reading and search tasks was predicted by a linear regression model and subsequently cross-validated by additional experiments.

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Evaluations of several specific flat panel displays were made, with operator performance predicted acceptably from the previously derived regression model of display quality.

Optimal capital alphanumeric fonts were determined for 5 × 7, 7 × 9, and 9 × 11 matrices.

TABLE OF CONTENTS

Section		Page
I.	INTRODUCTION	1
	Background	3
	Design Variables	6
	Display luminance	6
	Luminance contrast or modulation	6
	Element or dot size	10
	Dot size and interelement spacing	11
	Ambient illuminance	11
	Refresh rate	12
	Display chrominance	12
	Pertinent Literature	12
	Summary	18
II.	THE SENSITIVITY OF SEVERAL RESPONSE MEASURES TO DOT-MATRIX DISPLAY VARIABLES	20
	Introduction	20
	Accuracy	22
	Response time	22
	Tachistoscopic recognition	22
	Threshold visibility	22
	Method	22
	Display variables	22
	Experimental design	25
	Apparatus	26
	Data collection and reduction	28
	Observer response measures	28
	Results	32
	Accuracy	32
	Response time	34
	Tachistoscopic recognition	43
	Visibility threshold	47
	Comparison of response measures	50
	Discussion	51
	Display Parameters	55
	Character size	56
	Luminance	56
	Viewing distance	57
	Conclusions from this Experiment	58
III.	OPTIMAL ELEMENT SIZE-SHAPE-SPACING COMBINATIONS FOR A 5 × 7 MATRIX	60
	Introduction	60
	Font Selection	61

Section Page

Method 61
Experimental design 61
Element shape 64
Element size 64
Interelement spacing 66
Ambient illuminance 66
Subjects 66
Dependent measures 66
The Basic Reading Rate Scale 70
Laboratory equipment 75
Experimental area 75
Experimental procedure 76
Results 77
Tinker reading task 77
Random search task 80
Menu search task 88
Discussion 92
Tinker test 98
Random search task 99
Menu search task 99
Design Recommendations and Conclusions 100
Element size 100
Element shape 100
Interelement spacing ratio 100
Ambient illuminance 100

IV. PREDICTION OF INTELLIGIBILITY OF CONTEXTUAL AND NONCONTEXTUAL CHARACTERS: INITIAL EXPERIMENT 101

Introduction 101
Modulation Transfer Function (MTF) of the Eye 102
Display Parameters Critical to Power Spectrum Measurement . 104
Purpose of this Research 104
Method 105
Subjects 105
Apparatus 105
Contextual advantage 106
Viewing conditions 108
Fourier analysis 108
Procedure 109
Experimental design 110
Results 110
Context assessment 110
Spatial frequency analysis 116
Discussion 119
Evaluation of context advantage 119
Conclusions 126

V. PREDICTION OF INFORMATION TRANSFER FROM SIMULATED SOLID STATE DISPLAYS 128

Section Page

Introduction 128
Method 129
Experimental design 129
Observer tasks 131
Apparatus 131
Photometry 138
Analysis of photometric data 141
Derivation of the metric equations 145
Correction for matrix size 148
Results 148
Predictive metrics from phase one 148
Phase two verification 150
Validation of metrics 154
Discussion 156
Prediction metrics 156
Photometry evaluation 161
Summary and Conclusions 162

VI. VALIDATION OF PREDICTION EQUATIONS USING AC AND DC PLASMA PANELS 163

Introduction 163
Method 163
Subjects 163
Apparatus 164
Experimental design 164
Procedure 166
Photometric data 168
Results 169
Menu search 169
Reading time 171
Prediction of performance 173
Discussion 174
Conclusions 178

VII. FONT OPTIMIZATION FOR 5 × 7 DOT-MATRIX ALPHANUMERICS 179

Introduction 179
Method 180
Fonts 180
Apparatus 180
Subjects 182
Procedure 182
Results 183
Discussion 185
Conclusions 190

Section		Page

VIII. FONT OPTIMIZATION FOR 5 × 7, 7 × 9, AND 9 × 11 DOT-MATRIX ALPHANUMERICS 191

- Introduction 191
- Method 191
  - Subjects 191
  - Apparatus 192
  - Experimental design 193
  - Procedure 215
- Results 217
  - Number of errors 217
  - Confusion matrices 220

IX. EXTENDED PREDICTION MODEL 243

- Method 243
- Results 244
- Discussion 245

X. DISCUSSION 249

- Performance Measures and Tables 249
- Agreement with Previous Research 250
  - Character size 251
  - Dot size 251
  - Dot shape 252
  - Dot spacing 252
  - Dot luminance/modulation 252
  - Font selection 252
- Image Quality Metrics and Prediction 253
- Photometric Measurement 254
- One- *vs.* Two-Dimensional Photometry 254
- Remaining Research Questions 255
  - Font optimization 255
  - Model development 255
  - Paging displays 255

XI. SUMMARY AND DESIGN RECOMMENDATIONS 257

XII. REFERENCES 259

APPENDIX A, CELL MEANS 263

APPENDIX B, WORDS AND ANAGRAMS 266

APPENDIX C, REGRESSION PROGRAM OUTPUT 273

LIST OF ILLUSTRATIONS

Figure | Page

1. Alphanumeric Characters 24
2. Character Size Configurations 24
3. Character Dot-Matrix Configurations 24
4. Displayed Fixation Box 29
5. Character Presentation 29
6. Subject's Response Instructions 30
7. Effect of Character Size upon Accuracy 37
8. Effect of Character Size by Luminance Interaction upon Accuracy 37
9. Effect of Character Size upon Accuracy at Various Viewing Distances 38
10. Interaction of Character Size by Distance at 8 cd/m^2 38
11. Interaction of Character Size by Distance at 27 cd/m^2 39
12. Interaction of Character Size by Distance at 80 cd/m^2 39
13. Effect of Luminance upon Accuracy 40
14. Effect of Luminance by Viewing Distance Interaction upon Accuracy 40
15. Effect of Character Size upon Response Time 42
16. Effect of Luminance upon Response Time 42
17. Effect of Viewing Distance upon Response Time 44
18. Effect of Viewing Distance by Character Size Interaction upon Response Time 44
19. Effect of Character Size by Luminance Interaction at 16.67 ms Exposure Time 46
20. Effect of Character Size by Luminance Interaction at 50 ms Exposure Time 46
21. 50% Threshold Visibility Distances 49

Figure Page

22. 85% Threshold Visibility Distances 49

23. Composite 5 × 7 Font 62

24. Experimental Design 63

25. Element Size Dimension 65

26. Character "F" and Its Development 67

27. Smallest Spacing/Element Size Ratio Combination 69

28. Largest Spacing/Element Size Ratio Combination 69

29. Menu Search Task: Search Display and Location Number 72

30. Random Search Task: Random Search Display and Location Grid . 74

31. Effect of Element Size on Reading Time 79

32. Effect of Element Shape on Reading Time 79

33. Effect of Interelement Spacing Ratio upon Reading Time 81

34. Effect of Size × Shape × Illuminance Interaction upon Reading Time 81

35. Effect of Element Size upon Random Search Time 83

36. Effect of Element Shape upon Random Search Time 83

37. Effect of Ambient Illuminance upon Random Search Time 84

38. Effect of Size × Shape Interaction upon Random Search Time . . 84

39. Effect of Element Size by Illuminance Interaction upon Random Search Time 86

40. Effect of Element Shape by Illuminance Interaction upon Random Search Time 86

41. Effect of Size × Shape × Spacing Interaction upon Random Search Time 87

42. Effect of Size × Shape × Illuminance Interaction upon Random Search Time 87

43. Effect of Shape × Spacing × Illuminance Interaction upon Random Search Time 89

Figure | Page

44. Effect of Element Size upon Menu Search Time 91

45. Effect of Ambient Illuminance upon Menu Search Time 91

46. Effect of Character Size by Luminance Interaction upon Word Scores 113

47. Effect of Luminance upon Anagram Scores 113

48. Effect of Character Size upon Anagram Scores 115

49. Effect of Character Size by Luminance Interaction upon Anagram Scores 115

50. Effect of Character Size by Luminance Interaction upon Difference Scores 117

51. MTFA Concept 117

52. Correlation between Anagram Scores and Transfer Function Areas, Slit Aperture 120

53. Correlation between Anagram Scores and Transfer Function Areas, Circular Aperture 120

54. Correlation between Anagram Scores and Transfer Function Areas, Slit Aperture, Log_{10} Transformed 121

55. Correlation between Anagram Scores and Transfer Function Areas, Circular Aperture, Log_{10} Transformed 121

56. Correlation between Anagram Scores and Weighted Transfer Function Areas, Slit Aperture 122

57. Correlation between Anagram Scores and Weighted Transfer Function Areas, Circular Aperture 122

58. Correlation between Anagram Scores and Weighted Transfer Fucntion Areas, Slit Aperture, Log_{10} Transformed 123

59. Correlation between Anagram Scores and Weighted Transfer Function Areas, Circular Aperture, Log_{10} Transformed 123

60. Experimental Design 132

61. DIGIVUE Simulation, 5 × 7 Matrix Size 132

62. DIGIVUE Simulation, 7 × 9 Matrix Size 133

Figure Page

63. DIGIVUE Simulation, 9 × 11 Matrix Size 133

64. SELF-SCAN Simulation, 5 × 7 Matrix Size 134

65. SELF-SCAN Simulation, 7 × 9 Matrix Size 134

66. SELF-SCAN Simulation, 9 × 11 Matrix Size 135

67. TFT Simulation, 5 × 7 Matrix Size 135

68. TFT Simulation, 7 × 9 Matrix Size 136

69. TFT Simulation, 9 × 11 Matrix Size 136

70. Simulated Dot Parameters 137

71. Schematic of Photometer Interconnects 140

72. Flow Chart of Optimization Routine 142

73. Effect of Matrix Size upon Reading Time 151

74. Effect of Matrix Size by Dot Interaction upon Reading Time . . 151

75. Effect of Matrix Size upon Menu Search Time 153

76. Experimental Design 165

77. Effect of Display Type upon Menu Search Times 170

78. Effect of Display Type upon Corrected Reading Times 170

79. Maximum Dot, Maximum Angle, and Lincoln/Mitre Fonts 181

80. Number of Errors for Each Font 186

81. Confusion Matrix for Maximum Dot Font 187

82. Confusion Matrix for Maximum Angle Font 188

83. Confusion Matrix for Lincoln/Mitre Font 189

84. Experimental Design, Second Font Study 194

85. Huddleston Font in 5 × 7 Matrix 195

86. Huddleston Font in 7 × 9 Matrix 196

Figure | Page

87. Huddleston Font in 9 × 11 Matrix 197

88. Huddleston Font in 7 × 9(= 5 × 7 Size) Matrix 198

89. Huddleston Font in 9 × 11(= 5 × 7 Size) Matrix 199

90. Maximum Dot Font in 5 × 7 Matrix 200

91. Maximum Dot Font in 7 × 9 Matrix 201

92. Maximum Dot Font in 9 × 11 Matrix 202

93. Maximum Dot Font in 7 × 9(= 5 × 7 Size) Matrix 203

94. Maximum Dot Font in 9 × 11(= 5 × 7 Size) Matrix 204

95. Maximum Angle Font in 5 × 7 Matrix 205

96. Maximum Angle Font in 7 × 9 Matrix 206

97. Maximum Angle Font in 9 × 11 Matrix 207

98. Maximum Angle Font in 7 × 9(= 5 × 7 Size) Matrix 208

99. Maximum Angle Font in 9 × 11(= 5 × 7 Size) Matrix 209

100. Lincoln/Mitre Font in 5 × 7 Matrix 210

101. Lincoln/Mitre Font in 7 × 9 Matrix 211

102. Lincoln/Mitre Font in 9 × 11 Matrix 212

103. Lincoln/Mitre Font in 7 × 9(= 5 × 7 Size) Matrix 213

104. Lincoln/Mitre Font in 9 × 11(= 5 × 7 Size) Matrix 214

105. Effect of Font upon Numbers of Errors 219

106. Effect of Character/Matrix Size upon Numbers of Errors 219

107. Effect of Character/Matrix Size by Font Interaction upon Number of Errors 222

108. Confusion Matrix for 5 × 7 Lincoln/Mitre Font 223

109. Confusion Matrix for 7 × 9 Lincoln/Mitre Font 224

110. Confusion Matrix for 9 × 11 Lincoln/Mitre Font 225

Figure | Page

111. Confusion Matrix for 7 × 9(= 5 × 7) Lincoln/Mitre Font 226

112. Confusion Matrix for 9 × 11(= 5 × 7) Lincoln/Mitre Font 227

113. Confusion Matrix for 5 × 7 Huddleston Font 228

114. Confusion Matrix for 7 × 9 Huddleston Font 229

115. Confusion Matrix for 9 × 11 Huddleston Font 230

116. Confusion Matrix for 7 × 9(= 5 × 7) Huddleston Font 231

117. Confusion Matrix for 9 × 11(= 5 × 7) Huddleston Font 232

118. Confusion Matrix for 5 × 7 Maximum Dot Font 233

119. Confusion Matrix for 7 × 9 Maximum Dot Font 234

120. Confusion Matrix for 9 × 11 Maximum Dot Font 235

121. Confusion Matrix for 7 × 9(= 5 × 7) Maximum Dot Font 236

122. Confusion Matrix for 9 × 11(= 5 × 7) Maximum Dot Font 237

123. Confusion Matrix for 5 × 7 Maximum Angle Font 238

124. Confusion Matrix for 7 × 9 Maximum Angle Font 239

125. Confusion Matrix for 9 × 11 Maximum Angle Font 240

126. Confusion Matrix for 7 × 9(= 5 × 7) Maximum Angle Font 241

127. Confusion Matrix for 9 × 11(= 5 × 7) Maximum Angle Font 242

LIST OF TABLES

Table Page

1. Manufacturers' Specifications for Computer-Generated CRT Displays 7

2. Persistence Characteristics and Empirically Determined CFF of Phosphors Commonly Used on CRT Displays 13

3. Vertical Visual Angle Subtense 23

4. Pertinent Specifications for Tektronix Model 4014-1 Computer Display Terminal 27

5. Analysis of Variance Summary for Accuracy 33

6. Summary of Significant Sources of Variance for Recognition Accuracy 35

7. Analysis of Variance Summary for Response Time 41

8. Summary of Significant Sources of Variance for Response Time . . 43

9. Analysis of Variance Summary for Tachistoscopic Recognition Accuracy 45

10. Summary of Significant Sources of Variance for Tachistoscopic Recognition Accuracy 47

11. Analysis of Variance Summary for 50% Threshold Visibility . . . 48

12. Analysis of Variance Summary for 85% Threshold Visibility . . . 50

13. Sensitivity Comparisons of Operator Response Measures 52

14. Product-Moment Intercorrelations Among Response Measures for the 12 $C \times L$ Means 53

15. Percent Accountable Variation (Intra-Class Correlation) 54

16. Edge-to-Edge Dimensions of Character Matrices 68

17. Analysis of Variance Summary for Tinker Reading Test 78

18. Analysis of Variance Summary for Random Search Task 82

19. Analysis of Variance Summary for Menu Search Task 90

Table		Page
20.	(a) Character Subtense and Percent Active Area for the 0.76 mm Elements	94
20.	(b) Character Subtense and Percent Active Area for the 1.14 mm Elements	95
20.	(c) Character Subtense and Percent Active Area for the 1.52 mm Elements	96
21.	Correlation of Secondary Variables with Dependent Variables	97
22.	Analysis of Variance Summary for Word Scores	111
23.	Analysis of Variance Summary for Anagram Scores	111
24.	Analysis of Variance Summary for Difference Scores	112
25.	Pool of Predictor Variables	146
26.	Predictive Equations	149
27.	Analysis of Variance Summary for Tinker SOR Task	152
28.	Analysis of Variance Summary for Menu Search Task	154
29.	Predicted and Measured Performance Data (s)	155
30.	Summary of Analysis of Variance of Menu Search Task	171
31.	Summary of Analysis of Variance of Tinker SOR Scores	172
32.	Summary of Analysis of Variance of Corrected Tinker SOR Scores	172
33.	Comparison of Predicted, Simulated, and Final Performance Scores	173
34.	Comparison of Photometric Prediction Equation and Actual SELF-SCAN Performance Times	177
35.	Analysis of Variance of Errors for Three Fonts and Four Trial Blocks	184
36.	Summary of Analysis of Variance for Correct Responses	218
37.	Extended Prediction Equations	246
38.	Design Recommendations for Dot-Matrix Displays	258

FOREWORD

This final technical report covers research performed during the period 15 September 1974 through 31 August 1978. The research was supported by Grants DAFC04-74-G-0200 and DAAG29-77-G-0067 from the U.S. Army Research Office, Research Triangle Park, North Carolina. Dr. Jimmie R. Suttle, Director of the Electronics Division of ARO, was the Contracting Officer, while Dr. Elliott Schlam, USAECOM, Ft. Monmouth, provided valuable technical advice and information.

Although portions of this research have been or will be published in the open journal literature, it has been decided to collect the specific research results together in this comprehensive, albeit quite large, technical report because there is little comprehensive information available on the subject. To that end, it is hoped that this report can be read, in whole or in part, as the designer's needs require.

Many persons contributed greatly to this research program. For some, the research reported herein is a portion of their graduate degree requirements. Others were involved in the research as an integral part of their laboratory research duties and interests. To all, we extend our appreciation for dedicated effort, time, and thought. Contributors to this research are indicated below. When a degree was awarded, based on this research, it is also so noted, as is the nature of the contribution or report Section to which contribution was made.

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I. INTRODUCTION

In the past decade there has been an unprecedented increase in the number of computers in service at nearly every level of sophistication. Whereas the first and second generation computer systems were mammoth in both scope and price, there now exists a quite sizeable market in the world for smaller, less expensive computers. Whether one speaks of mini-computers, micro-computers, or any other size-related term, the fact borne out by industry figures is that the number of systems capable of data input, manipulation, and output is increasing rapidly.

There are many implications, both philosophical and practical, which can be drawn from the rapid and, as yet, unslowed proliferation of devices capable of high speed data manipulation and information presentation. However, the present research is concerned with the fact that somewhere in the chain of computers and computer peripherals a link with the human element must be made. It is true that some computer applications do not require direct human intervention. An example of this might be a closed-loop automatic process control system utilizing direct digital control. On the other hand, a great many computer systems require a human operator to enter data into the machine, monitor data output from the machine, or both.

Some computer peripherals are designed to make a hard copy of the computer output. Examples of this type of peripheral are line printers and microfiche output machines. With this type of output, the human operator or observer is able to evaluate the information at his leisure. Much research has been done to specify optimal qualities of printed typography. Such research is more or less directly transferable to hard copy computer output devices.

The increasing use of interactive, or conversational, computer systems and the expanded use of systems with volatile output information has spawned a relatively new type of computer peripheral known as a computer-generated dot-matrix display. These displays are characterized by a cathode-ray tube or some solid-state device upon which all alphanumeric and vector-graphic information is made up of some combination of small dots. Generally the dots are illuminated spots on a darker background, although displays do exist which reverse this information/background contrast relationship.

The purpose of this research program is to derive predictive metrics for information transfer for computer-generated dot-matrix displays. Predictive metrics, in this sense, are equations which predict observer performance on the basis of quantitative display parameters. The research is directly applicable to displays which do not exhibit a television-like raster. However, many dot matrix displays which actually use a raster are operated with a modulation which renders the raster structure invisible. Thus, the metrics derived from this research are useful for any dot matrix display which does not generate a visible raster structure.

This final technical report describes the major research efforts conducted under this program during the three-year funding period.

It describes pertinent background research and concepts, early laboratory investigations of the effects of specific dot-matrix design variables upon character legibility, two research studies of dot-matrix font comparison and optimization, an empirical study comparing three commercially available dot-matrix display panels, and the results of a study to derive predictive equations of dot-matrix character legibility.

As a result of the numerous studies conducted under this program and of the large amount of empirical data, this final technical report is quite lengthy. However, in view of the design importance of these data and of the historical lack of pertinent design information, it was decided to publish this as a detailed technical report rather than as a superficial summary report. It is hoped that the results of the studies described herein will be used by the display community as both design guidelines (which are sorely needed) and as stimuli for the direction of further research.

Background

Dot-matrix displays are distinguished from other types of displays by the configuration of small dots which make up the symbols presented to the observer. In contrast to these dot-matrix characters are the so-called stroke or continuous characters which are used in normal print or type. That dots normally compose the symbols in a computer-generated display is a direct result of either the display device hardware or the digital nature of computers and the circuitry associated with their peripherals. If the display surface is considered to be composed of a number of discrete points, then each point may be given some type of an address much like the memory locations within the computer itself. When a symbol is to be generated, the addresses of the points which make up that symbol are read out of some type of memory and these points are then illuminated. The resultant circuitry is much less complicated than that of a comparable vector or stroke character generator.

Thus, dot-matrix displays would appear to be a logical extension of the digital nature of computers in general. Unfortunately, when the designer of a dot-matrix display is confronted with satisfying some specification for readability, legibility, or some other parameter of such a display, a rather surprising fact surfaces. A voluminous body of experimental knowledge exists on the effect of certain display parameters on readability. Most of these experimental data exist for stroke characters, however, and suitable design data for dot-matrix displays are quite sparse.

The literature on dot-matrix displays is equivocal even on the question of the relative legibility of dot *vs.* stroke characters. Research has suggested that, under certain conditions, dot-matrix character construction is superior in legibility to stroke symbol generation (Semple, Heapy, Conway, and Burnette, 1971; Vartabedian, 1971). Other research has indicated that stroke symbols are superior under adverse conditions and that no significant difference exists in a more normal viewing situation (Shurtleff, 1974).

Dot-matrix and stroke characters share many parameters, such as character size, luminance, luminance contrast, aspect ratio, font, and percent active area. In addition, dot-matrix characters introduce several within-character parameters not found in other types of symbology. These parameters include dot size, dot shape, dot spacing, and number of dots. It should be noted that all of these parameters are not independent. For instance, if dot size, dot spacing, and number of dots are fixed, then the character size, aspect ratio, and percent active area are automatically set.

Sufficient experimental data exist to allow a fairly quantitative assessment of the effects on operator performance due to levels of some display parameters (Gould, 1968; Howell and Kraft, 1959). In addition, many researchers have contributed experimental data on certain aspects of dot-matrix displays. Typically, studies of dot-matrix symbology vary several display parameters while holding the remainder constant. This is done as an expediency, since a factorial experiment involving all dot-matrix parameters would be prohibitively large. Among those parameters investigated have been font (Huddleston, 1974; Kinney, Marsetta, and Showman, 1966; Shurtleff, 1970), number of dots (Shurtleff, 1974), dot shape and character orientation (Vartabedian, 1971), and character size and luminance (Taylor, 1975). Perhaps the most extensive previous study of dot matrix display parameters was done at Hughes Aircraft Company in 1974 (VanderKolk, Herman, and Hershberger, 1974). Much of this research was based on a literature review and analysis done by Semple, *et al.* (1971). Among the display attributes studied were contrast, resolution (number of dots), surround luminance, percent active area, symbol subtense, and viewing angle. The nature of these more important design variables and representative results are briefly summarized below.

Design Variables

Display luminance. Most computer terminals of the CRT variety produce a maximum luminance of at least 65 cd/m^2 with some as much as 350 cd/m^2. Any display luminance above about 65 cd/m^2 is probably adequate, assuming that the ambient illumination is such that sufficient contrast is maintained between the displayed characters and their background. Manufacturers' specifications for computer-generated alphanumeric cathode-ray tube (CRT) displays are noted in Table 1 (Gould, 1968). It must be recognized that there is a fundamental trade-off between luminance and spot size of any CRT. As luminance is increased, the spot size tends to spread and results in a more gradual edge gradient for any character. This causes a reduced subjective impression of sharpness and contrast. Also, increasing luminance by increasing beam current can reduce the useful life of the CRT and should be avoided.

In comparison, matrix display luminance is typically about 170 cd/m^2 (Reingold, 1974). Therefore, for research purposes, most CRT displays could be used to simulate the luminances produced by dot-matrix displays, assuming other requirements can be met.

Luminance contrast or modulation. One of the more general equations for defining luminance modulation, M, is:

TABLE 1. Manufacturers' Specifications for Computer-Generated CRT Displays (adapted from Gould, 1968)

Model	*Phosphor*	*Color*	*Luminance* (cd/m^2)	*Contrast Ratio*	*Spot Diam.* (*mm*)
BR-90	P-4	wh, wh	68	15:1	0.51
CDC-250	P-31	gr, gr	--	10:1	0.89
CDC-273	P-7	w, y-g	--	--	0.51
CDC-1744	P-7	w, y-g	--	--	0.51
DEC-338 & 340	P-7	w, y-g	--	--	0.38
Elliot-4280	L-3, Q-4	org, viol	68	30:1 (filter)	0.38
Ferranti Argus 30 and 40	L-4	org, y	68	4:1	0.61
IDI-10,000 and 11,000	P-31	gr, gr	135	5:1	0.25
III-1050	P-31	gr, gr	--	--	0.51
IBM-2250	P-7	w, y-g	--	--	0.51
ICT-1830	L-3, Q	org, viol	--	--	0.20
IDI-IOM	P-31	gr, gr	135	5:1	0.25
ITT Modular	P-4	wh, wh	125	5:1 min	0.53
Philco Read	P-28	y-g, y-g	340	20:1	0.38
RCA-6320	P-4A	wh, wh	--	y:1	0.25
Raytheon-1500	P-31	gr, gr	100	30:1	0.51
Telefunken 200-4	P-2	y-g, y-g	--	--	--
SDS-9185	P-31	gr, gr	--	--	0.51
S-C-1090	P-28	y-g, y-g	68	100:1	0.64
SEL-80-816	P-31	gr, gr	--	--	0.36
Tasker	P-1	y-g, y-g	340	--	0.46

TABLE 1--*(Continued)*

Model	Regeneration Rate (Hz)	Method of Generating Lines	Method of Generating Char.	Display Size (cm^2)	Number Addressable Points
BR-90	60 max.	stroke	stroke	1124	1024^2
CDC-250	60 prog.	stroke	stroke	929	1024^2
CDC-273	30	stroke	n/a	2077	4096^2
CDC-1744	40 max.	stroke	n/a	2077	4096^2
DEC-338 & 340	30	point	point	567	1024^2
Elliot-4280	10	stroke	point	645	1024^2
Ferranti Argus *30 and 40*	16-2/3	stroke	stroke	1239	1024 × 768
IDI-10,000 and 11,000	30	stroke	stroke	1090	1024^2
III-1050	30	stroke	stroke	645	1024^2
IBM-2250	40 prog.	stroke	stroke	929	1024^2
ICT-1830	10 prog.	stroke	stroke	645	1024^2
IDI-IOM	30 select	stroke	stroke	1090	1024^2
ITT Modular	40 max.	stroke	stroke	929	1024^2
Philco Read	60 max.	stroke	stroke	523	1024^2
RCA-6320	60	stroke	stroke	929	1024^2
Raytheon-1500	48	stroke	stroke	929	512^2
Telefunken 200-4	60 max.	stroke	stroke	2581	512^2
SDS-9185	30	stroke	stroke	645	1024^2
S-C-1090	30 prog.	stroke	stroke	1045	512^2
SEL-80-816	60 prog.	stroke	stroke	523	643^2
Tasker-9000	50	stroke	stroke	1468	2084 × 1404

$$M = \frac{L - D}{L + D} \quad (1)$$

where

L is the maximum luminance (i.e., symbol luminance on CRT), and

D is the minimum luminance (i.e., background luminance on CRT).

In typical computer-generated display operations, the display is viewed under ambient levels of about 540-1080 lux. The ambient illuminance produces a reflected luminance on the display, L_e, which is added to both the character luminance and the background luminance. Therefore, a more realistic equation for defining luminance modulation, M, is provided by Gould (1968):

$$M = \frac{(L_i + L_e) - (D_i + L_e)}{(L_i + L_e) + (D_i + L_e)}$$

$$= \frac{L_i - D_i}{L_i + D_i + 2L_e} \quad (2)$$

where

L_i is the internally produced symbol luminance, and

D_i is the internally produced background luminance.

The maximum luminance modulation on CRT displays is typically 0.90 (Gould, 1968) and this is rarely obtained without the use of filters of one form or another (neutral density, polarized, circularly polarized, etc.) to reduce the reflected ambient illuminance. Studies by Howell and Kraft (1959) have recommended a desirable luminance modulation of 0.94 and an acceptable luminance modulation of 0.88 for alphanumeric characters that are relatively blurred due to the gradual, rather than sharp, symbol-to-background luminance gradients. Gradual luminance gradients are usually a result of increasing the spot size or increasing the maximum luminance.

One distinct advantage of the dot-matrix display is that the spot size is governed by the size of the matrix cell and little halation is obtained. Therefore, the dot-matrix energy gradient is quite steep compared to the conventional CRT, even under the best CRT conditions.

Element or dot shape. Vartabedian (1970) showed that element shape can be a determinant of subjects' performance. He found that elliptical elements were inferior to circular elements in speed and accuracy of identification measures. As VanderKolk, *et al.* pointed out, "the eye can integrate luminous flux over a finite area" (p. 120), so the effect that element shape has on legibility is probably one of luminous density. Hence, circles are more luminous per some finite area than are triangles that can be inscribed within the circles, for example, and should be more detectable. Casperson, as VanderKolk, *et al.* stated, found that rectangles are more detectable than are squares. Gould (1968), Biberman (1973), Groves (1973), and Thompson (1957), as reported in VanderKolk, *et al.*, all have stated that simulated stroke characters, i.e., characters with no perceptible spaces between adjacent elements, are better than discrete element characters. This would imply that elongated, relatively less dense elements are better if oriented vertically to minimize spacing. Vartabedian (1970), contrary to Gould, Biberman, Groves, Thompson, and Semple, *et al.*, stated that circular elements are superior to elongated elements for accuracy and speed of identification, at least for CRT applications. As Ketchel and

Jenny (1968) summarized, there can be little doubt that element shape, at the least, interacts with other variables in determining character or symbol legibility. This interaction was explored in the present research.

Dot size and interelement spacing. Element size and interelement spacing have been studied from several approaches. Actually, there are three interdependent variables; the third variable is overall character subtense. Setting the sizes of any two of these variables will automatically and inevitably set the size of the third.

Howell and Kraft (1959) used overall subtense to study legibility of stroke characters projected on a ground glass screen. Their results indicate that 16.4 minutes of visual arc were sufficient for 97% accuracy of identification. Shurtleff, Marsetta, and Showman (1966) determined that up to 36 minutes of arc might be required for equivalent performance on a raster display. Ellis, Burrell, Wharf, and Hawkins (1974) showed that a dot-to-space ratio of 2:1 was preferable to a ratio of 1:1 when total luminance (integrated over the entire character) for both types of characters was equal. This means that a character composed of larger, dimmer elements is more legible than a character of smaller, brighter elements (assuming the same overall character size). More data on these interactions are contained in the present report.

Ambient illuminance. Carel (1965) showed that if the ambient illuminance at the display is more than 10 times greater than the display's background illuminance, and if the operator is adapted to this ambient illuminance level, symbol-to-display-background contrast ratios must be significantly greater than when the ambient-to-display-background contrast ratio is less than 10. As indicated above, the effect of ambient illuminance is generally to reduce displayed luminance contrast. This environmental variable is further explored in the present research.

Refresh rate. The presence of flicker in a display is annoying and usually interferes with information extraction from any changing or static display. Persistence characteristics and empirically determined critical flicker frequencies (CFF) of phosphors commonly used on computer-generated CRT displays are shown in Table 2 (Gould, 1968). It can be seen that relatively high computer bandwidths are necessary to generate even a few hundred characters on the typically used P31, P4, and P7 phosphors.

Display chrominance. CRT displays come in various phosphors, each having its own characteristic chromaticity coordinates and persistence values. Although most existing or planned dot-matrix displays have a predominantly orange-red chromatic appearance, there are green and yellow-green displays in prototype and design stages.

In terms of visual efficiency, it is desirable to have a hue in the green or yellow-green region simply because the eye is maximally sensitive to wavelengths around 540 to 550 nanometers. Also, some observers find a reddish display annoying after a long viewing period.

Pertinent Literature

While the above discussion compares various sources of information relative to specific display design variables, it may be helpful to the

TABLE 2. Persistence Characteristics and Empirically Determined CFF of Phosphors Commonly Used on CRT Displays (adapted from Gould, 1968)

	Residual Light after		Persistence to 10%	Empirically Determined CFF (small fields, Hz)					
				Turnage (1966)			Bryden (1966)	Mitchell & Resnick (1960)	
Phosphor	*1/30 sec*	*1/60 sec*	*(sec)*	*34 cd/m^2*	*110 cd/m^2*	*340 cd/m^2*	*170 cd/m^2*	*37 cd/m^2*	*184 cd/m^2*
P-28	85	90	550×10^{-3}	34	40	46	34.1		
P-19	80	90	220×10^{-3}				17.5		
P-12	70	85	210×10^{-3}	25	29	32			
P-7 (Y)	45	80	400×10^{-3}	32	38	43	29.8 (B&Y)		
P-1	4	23	24.5×10^{-3}	33	38	43	29.2	32	38
P-4 (Y)	1.3	7	60×10^{-6}	35	41	47	33.5 (B&Y)	36	43
P-31	1	1	38×10^{-6}	37	44	51	32.4		
P-20	1	1	50×10^{-6} to 18×10^{-3}	40	47	54	32.7		

reader to have a brief summary of the more pertinent experimental literature. The following short summary of several of these legibility studies outlines which display variables have been studied and the range over which these variables were evaluated. It also shows the types of response measures used and emphasizes the confusion and ambiguities in the reported results.

In a preliminary study of dot-matrix characters, VanderKolk, *et al.* varied dot size from 0.13 to 0.51 mm and distance between dots from 0.13 to 0.51 mm. A 5 × 7 dot matrix was compared to an 8 × 11 dot matrix. Single computer-generated letters were presented in non-contextual form, and response time and accuracy were measured. The parameters that were found to have significant effects were percent active area, symbol definition, surround luminance, contrast, and symbol subtense.

Shurtleff and Owen (1966) compared the legibility of the Courtney alphanumeric characters to those of the standard Leroy symbols displayed on a CRT at vertical resolutions of 12, 10, 8, and 6 scan lines per symbol height. The characters were presented in non-contextual form with speed and accuracy as the performance measures. The width-to-height ratio of the characters was 0.75. The characters had an average display luminance of 69 cd/m^2 with a background luminance of 5.2 cd/m^2. The characters were formed by solid strokes and subtended 16 min of visual angle at the subject's eye. The results showed that, at any reasonable value, identification of Courtney characters did not surpass that for the Leroy characters. The study supported the findings of other experiments, i.e., that resolution of 10 lines per symbol height remains the minimum value recommended for CRT display.

Giddings (1972) also performed a legibility study on the height of alphanumeric characters to be presented on CRT displays. The character heights used were 6.35, 4.75, 3.96, 3.18, and 1.59 mm. At a viewing distance of 76 cm, these characters subtended, respectively, 28, 21, 18, 14, and 7 min of visual angle at the subject's eye. The mean contrast ratio of the display was 10:1 with a mean character luminance of 747 cd/m^2. Accuracy and relative performance time were used as performance measures; the characters were presented both in contextual (6-letter words) and non-contextual (single) form. Giddings found no monotonic relationship between legibility and character (display) area. Small size characters caused legibility to decrease. At the same time, some larger sized characters also caused legibility to decrease. The optimum character height for alphanumerics presented in non-contextual form was found to be 4.75 mm.

Vartabedian (1971) performed a legibility study to evaluate symbol generation method (dot matrix *vs.* stroke matrix), dot matrix size (5 × 7 *vs.* 7 × 9), dot geometry (circle *vs.* vertically elongated dots), and symbol orientation. Alphanumeric characters were displayed in a non-contextual form in the center of the CRT display with a character spot luminance of 38 cd/m^2 and a background luminance of 6.9 cd/m^2. The viewing distance was fixed by a head rest at 71 cm. Characters were 3.56 mm in height and subtended 17.2 min of visual angle at the subject's eye. The width-to-height ratio of a nominal width symbol was set at 0.75. Response time and accuracy were the performance measures made on the basis of recognition. Vartabedian found that the 7 × 9 circle dot-matrix font was superior to all other fonts; that vertical dot elongation adversely affected legibility; that the 7 × 9 dot-matrix was superior to the 5 × 7 dot-matrix font; and that dot-matrix construction was superior in legibility to the stroke-matrix construction.

Shurtleff (1974) evaluated the legibility of characters formed in the Lincoln/Mitre font style. Alphanumeric characters were presented under two viewing conditions. First, the characters were presented with a visual size of 22 min of visual angle (this size represented the "optimal" displayed size). Then the characters were presented with a visual angle of 6 min (to represent a "degraded" displayed size). Shurtleff found that performance was poorer when viewed under "degraded" display conditions. He also found that performance changed very little for matrix sizes larger than 5 × 7. This conclusion was based on the use of reaction time as a performance measure. When the performance measure was changed to correct recognitions per minute, it was found that the 7 × 11 matrix gave better legibility results than did the 5 × 7 matrix. Shurtleff also compared 5 × 7 and 7 × 9 stroke-matrix characters against 7 × 11 dot-matrix characters of the same font style (Lincoln/Mitre). It was found that stroke-matrix characters were superior to dot-matrix characters only for conditions where characters were overprinted. When there was no character overprinting, there was no difference between the two matrix types.

Huddleston (1974) performed two studies to evaluate the effect of character size on the legibility of a British styled font (REA) compared to the font developed by Vartabedian (1971). During the first study, observer viewing distance was 193 cm with the observer's eye approximately 28 cm above centerline. Each character was 20.3 mm high and appeared at a luminance of 15.4 cd/m^2 against a background of 12 cd/m^2. The number of errors in reading the character was used as a performance measure. The REA font was reported to have better legibility than the font used by Vartabedian. During the second experiment, Huddleston presented characters that were 3.3 cm high with a display luminance of 8.6 cd/m^2 against a background of 6.9 cd/m^2. The same character fonts (REA and Vartabedian) were viewed at four distances ranging from 21 to 41.3 cm. The average number of character misreadings was again used as a performance measure, and the REA font style was still found to provide better legibility.

Howell and Kraft (1959) performed a study to evaluate the effects of size, blur, and contrast on the legibility of alphanumeric characters presented on CRTs. They used a photographic technique to simulate the presentation of characters on a CRT. The primary criterion of legibility was the rate of information transmission that was developed from speed and accuracy performance measures. The alphanumeric characters had a width-to-height ratio of 0.53. The characters were presented in a Mackworth-style font, under four levels of size, five levels of contrast, and three levels of blur (defined as the rate of transition between the luminance of symbols and that of their background). The results demonstrated that characters need to be larger than approximately 16 min of visual angle before any practical degree of legibility can be obtained. However, a character size greater than 16 min of visual angle only showed substantial improvements in legibility for characters that were degraded (reduced contrast or increased blur). They found that 27 min of visual angle was the breakpoint of the zone of maximum legibility. For characters of this size or larger, the effects of blur and contrast were relatively insignificant. The study also showed that contrast should be greater than 86% when no blur exists and the character size is 27 min of visual angle. They reported that the interactions of size, blur, and contrast are significant and the level of each of these parameters should be adjusted in accordance with the fixed values of the other parameters to obtain maximum legibility.

Summary

In sum, the pertinent background literature exhibits numerous shortcomings relative to the optimal design of dot-matrix, computer-generated displays.

First, the data on alphanumeric character legibility are adequate for stroke characters such as those seen in printed text. (For an excellent summary of this literature, see Cornog and Rose, 1967). Unfortunately, the few studies comparing stroke character legibility with dot-matrix character legibility are inconsistent in their conclusions and inadequate as design guidelines.

Second, several of the design variables important to present and future dot-matrix display technologies have not been adequately addressed and experimentally evaluated. More research is clearly required.

Third, there is some ambiguity in the literature due to the various performance criteria used by the numerous investigators.

Conflicting results and conclusions may be due to the inconsistent selection of these performance criteria.

Fourth, additional information on the optimal matrix size and font is sorely needed. Because matrix size and font interact, these variables must be studied simultaneously.

Last, it is desirable to derive some summary measure of display image quality for dot matrix displays as we have for imaging displays (Biberman, 1973). Research along these lines is also needed for guidance in future display prototype development.

These needs are all addressed in the following sections of this report. Specific experiments are collected by research objective for easier assimilation by the reader. A final summary section indicates what data gaps exist and what design guidelines are valid at the present time.

II. THE SENSITIVITY OF SEVERAL RESPONSE MEASURES TO DOT-MATRIX DISPLAY VARIABLES

Introduction

It is evident from the above literature summary that confusion exists in the interpretation of data collected for the purpose of defining legibility of alphanumeric characters presented on CRT displays. The general conclusions drawn from these parametric studies have been based on data collected using a variety of performance and response measures. The response measure and its definition are usually chosen by the investigator to fit his particular research objective or equipment. It is, therefore, important for investigators to choose response measures and define them in such a way that they can be replicated by other investigators without any ambiguities in their results. Moreover, it appears that the choice of a response measure can significantly affect the conclusions drawn from an experiment. Some response measures may be sensitive to certain display parameters, while other response measures may not.

One definite example of the ambiguity involved in the choice of the proper response measure can be found in the study reported by Huddleston (1974). In his discussion, Huddleston quotes Gibney's (1968) argument that isolated investigations, using tachistoscopic presentation, make harsh judgments of symbols which may be quite acceptable in the context of truly operational conditions and procedures. Huddleston also defends the use of tachistoscopic presentation but admits to the possibility of confusion in using different response measures. He states that variables which affect the presentation of characters (such as vibration, display luminance, character contrast, and the possible need for wide angle viewing of one display by more than one operator at a time) make it hard to find a reasonable performance measure and method of presentation that are compatible.

Over and above any selection of response measure based on the above considerations, it is also important that the selected response measure(s) have some operational or system meaningfulness. As pointed out by Chapanis (1971), the useful application of human performance data to system design centers around the selection of appropriate criteria of performance. That is, the response measure selected for measuring human performance in the system must also be pertinent to the criteria of system performance.

Accordingly, the research reported in this section evaluated the sensitivity of three typical response measures to variations in the character size (dot size and dot spacing) and dot luminance of a dot-matrix display. Photometric verification of all display parameters was made to assure valid generalization to dot-matrix hardware, while the results provide useful sensitivity indices for subsequent research needed to relate these and other critical design parameters to information transfer.

Specifically, this experiment determined the effectiveness of four response measures (threshold visibility, tachistoscopic recognition, response time, and recognition accuracy) in a single-character recognition task. In addition, the study provided some useful tradeoff data among contrast, size, and viewing distance for dot-matrix characters.

These response measures are defined as follows.

Accuracy. Accuracy is defined as the proportion of correct responses that the observer makes when viewing randomly presented alphanumeric (or other) characters at the normal viewing distance of the display.

Response time. Response time measures the speed with which the observer responds correctly to a single alphanumeric character. Response time begins with the presentation of the character and ends with the observer's overt recognition response.

Tachistoscopic recognition. Tachistoscopic recognition is measured as the number (or proportion) of correct recognitions that the operator makes when viewing alphanumeric characters that are presented randomly on the display for a (typically) few milliseconds.

Threshold visibility. As a response measure, threshold visibility is related to the distance at which alphanumeric characters can be identified at a certain fixed percent level. Threshold visibility is measured in a recognition task and is used to evaluate the operator's performance at different viewing distances from the display.

Method

Display variables. The display variables investigated included four character sizes, three luminances, and seven viewing distances.

The character sizes were developed from different dot size and interdot spacing combinations, as follows.

The 36 upper-case alphanumeric characters used in this research are shown in Figure 1. The heights of these displayed characters, which depend on the fixed values of the interpoint distance and point size, are 2.64, 3.05, 4.79, and 5.44 mm. The vertical visual angles subtended by these characters at the different viewing distances are shown in Table 3.

TABLE 3. Vertical Visual Angle Subtense (min of arc)

Character Size (mm)	*Distance Levels (m)* 0.61	1.07	1.52	1.98	2.44	2.90	3.35
2.64	14.90	8.51	5.96	4.58	3.72	3.14	2.71
3.05	17.19	9.82	6.88	5.29	4.30	3.62	3.13
4.79	27.00	15.43	10.80	8.31	6.75	5.68	4.91
5.44	30.65	17.52	12.26	9.43	7.66	6.45	5.57

The Tektronix 4014-1 display used in this research program has 4096 × 3072 locations that can be individually addressed by the computer. These individual locations may be turned "on" or "off" to form different characters or symbols. The nearly circular "minipoint" size is 0.20 mm. The centerline-to-centerline distance between adjacent minipoints is on the order of 0.089 mm.

This experiment used two different dot sizes. The first dot size was essentially one minipoint, with a diameter of 0.20 mm. The second dot size was formed by two circular 0.25 mm points arranged

Figure 1. Alphanumeric Characters

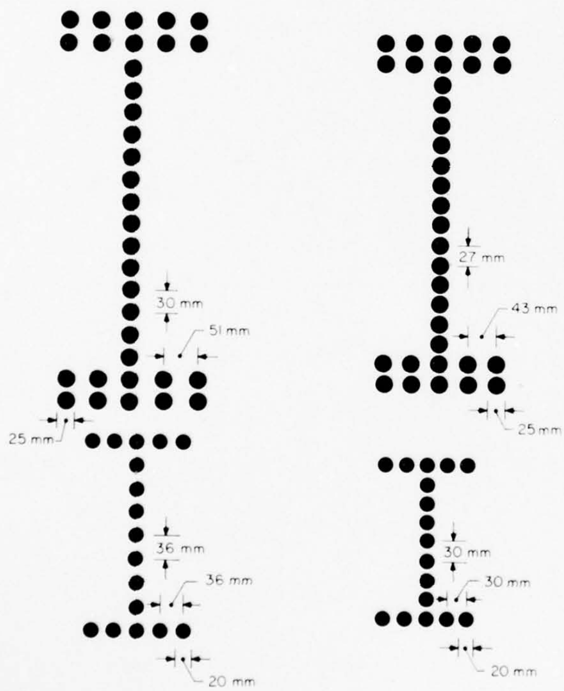

Figure 2. Character Size Configurations

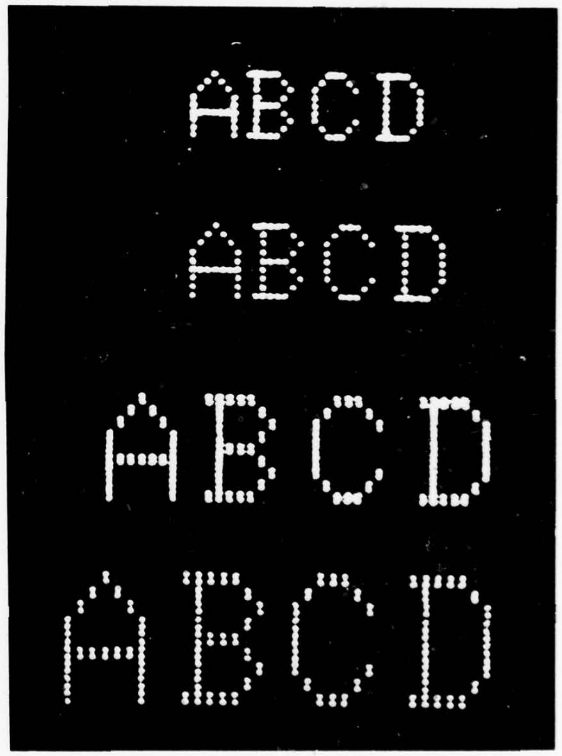

Figure 3. Character Dot-Matrix Configurations

vertically. Figure 2 schematically presents these point sizes, while Figure 3 shows the actual character configurations.

The matrix size that was used in this research was a 7 × 9 dot matrix. The width-to-height ratios of the four characters (smallest to largest) presented in this 7 × 9 dot matrix arrangement were 0.769, 0.767, 0.594, and 0.608. Note that each of the nine vertical "dots" for the two largest character sizes is actually a "double" dot.

Three levels of display luminance (8, 27, and 80 cd/m^2) were used. A Gamma Scientific Model 2400 Digital Photometer was used to measure the three luminance levels at each of the character sizes. A 450-micron aperture eyepiece, in conjunction with a 2.5X objective lens, was used to determine the luminance level of representative points within this 450/2.5 = 180-micron (diameter) object plane circular area.

Experimental design. Six paid subjects (three males and three females) from the University population were screened for normal color vision and corrected near and far acuity (20/22 or better in each eye) using a Bausch and Lomb Orthorater. Subjects' ages ranged from 20 to 28 years. Each subject received every level of each independent display variable.

For the accuracy and response time measures, the six subjects were assigned to all combinations of three luminance (L) levels and four alphanumeric character sizes (C) at each of seven different viewing distances (D). Each subject was presented 18 randomly-chosen alphanumeric characters under each experimental combination of L, C, and D.

The randomness of these presentations was constrained so that each of the 36 alphanumeric characters was presented three times per experimental condition, summed over all six subjects. A computer program was written to generate these random presentations.

To obtain the tachistoscopic recognition data, each of the six subjects was given each combination of three luminances and four character sizes. The alphanumeric characters were presented at three different exposure times, 16.67, 33.33, and 50 milliseconds. Each subject was presented 12 randomly-chosen alphanumeric characters at each of the three exposure times. The randomness of these presentations was constrained so that each of the 36 alphanumeric characters was presented twice per exposure time under each experimental combination of C and L, summed over the six subjects.

The data collected for the recognition response measure were also used to determine the 50% and 85% threshold visibility viewing distances for all 12 $C \times L$ combinations.

Apparatus. The CRT display terminal used in much of this research program, a Tektronix 4014-1, has the specifications contained in Table 4. For the purpose of this experiment, the display was operated as a computer-driven peripheral device in the write-through (alpha) mode. Also, the special purpose Tektronix polarizing filter was removed from the display surface.

The display was driven and controlled by a Digital Equipment Corporation PDP 11/10 minicomputer. Its fundamental characteristics include 24K words of memory; a removable cartridge disc unit, each cartridge having a storage capacity of 1.2M words; and a bootstrap loader to facilitate starting the system.

TABLE 4. Pertinent Specifications for Tektronix Model 4014-1 Computer Display Terminal

Display Medium:	direct view storage CRT tube
Display Size:	38 cm wide by 28 cm high
Alphanumeric Mode:	four program-selectable formats, ranging from 74 characters per line with 35 lines per display to 133 characters per line with 64 lines per display.
Character Set:	full ASCII character set
Vector Mode:	drawing time 102 m per second; 1024 × 1024 addressable points
Discrete Plot Mode;	4096 × 4096 addressable points (12 bits); 4096 × 3120 displayed points
Writing Modes:	storage mode and write-through
Phosphor Chrominance:	green (P43)

A Documation 150-D optical character card reader was interfaced with the minicomputer to provide input at the rate of 150 cards/min. This device was used to input programs from computer cards that presented the trials to the subject.

A Teletype Corporation TTY was also interfaced with the minicomputer. Its data transmission rate is 10 characters/s. It is equipped with a paper tape reader and punch, and it was operated both as a hard copy console and as a peripheral device to control experiments.

The computer and its peripherals, exclusive of the CRT terminal, were located in one room. The CRT terminal was located in an adjacent room. The subject, seated at the terminal, could converse with the experimenter, seated at the computer, through an intercom.

Data collection and reduction. Data collection was controlled by the minicomputer. At the end of the experiment, data reduction analyses were performed by the computer.

Observer response measures. The four response measures used in this research were accuracy, response time, tachistoscopic recognition, and threshold visibility.

At least 14 training trials were completed by each subject prior to actual data collection. This training allowed the subject to become familiar with the equipment and instructions, and to ask any questions that he/she might have concerning his/her responsibilities during the experiment.

Upon arriving for an experimental session, the subject was seated in a dark room in front of the CRT display at the 0.61 m viewing distance. When he/she was ready to begin the experiment, he/she would press a hand-held button. Instructions were then displayed to the subject on the terminal. The subject was instructed to press the button to initiate each trial, and to press the button as soon as he/she recognized the alphanumeric character. Both speed and accuracy were stressed as important factors in the performance of the subject.

If the subject had no questions concerning the experiment, the chair was moved to the previously selected viewing distance. When the experiment began, a fixation box was displayed on the CRT with instructions to the subject (see Figure 4). The subject was asked to

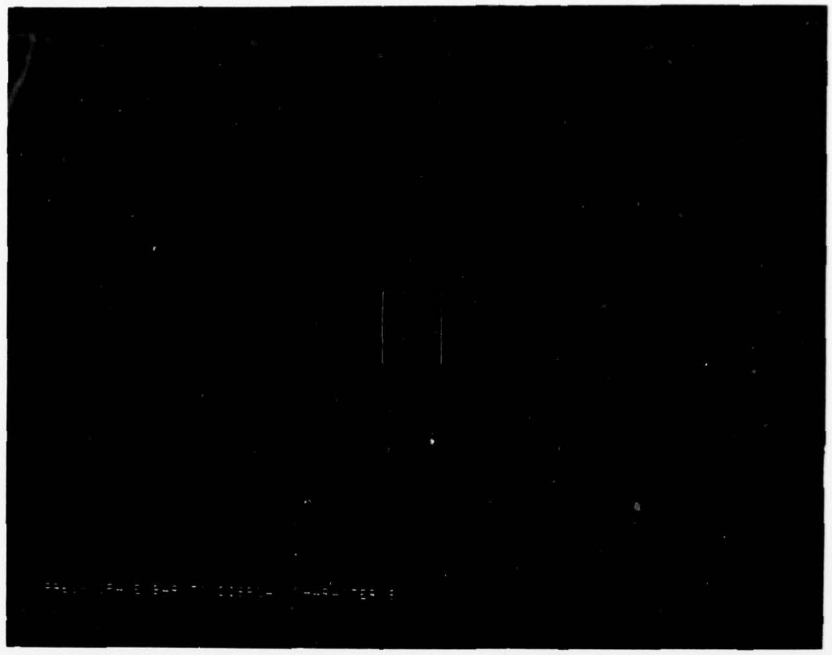

Figure 4. Displayed Fixation Box

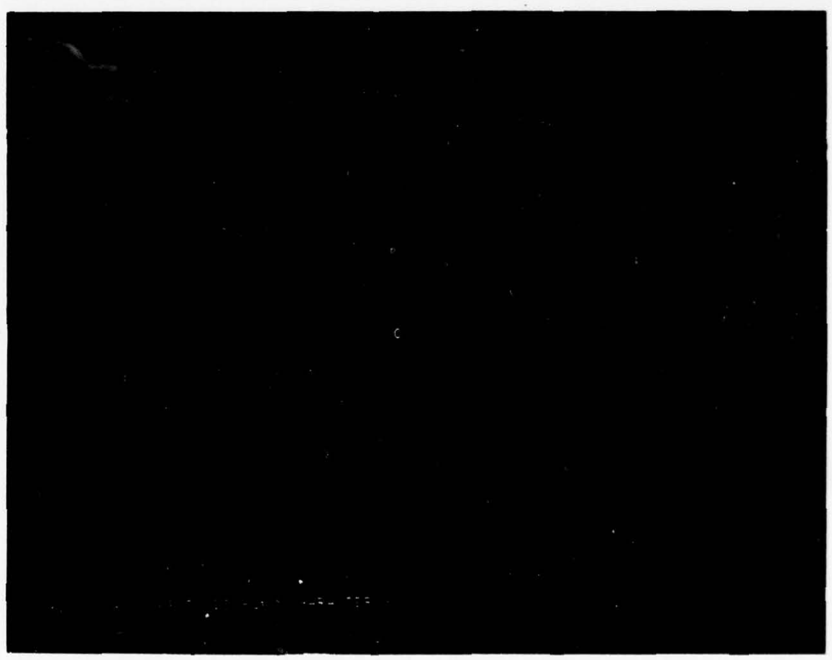

Figure 5. Character Presentation

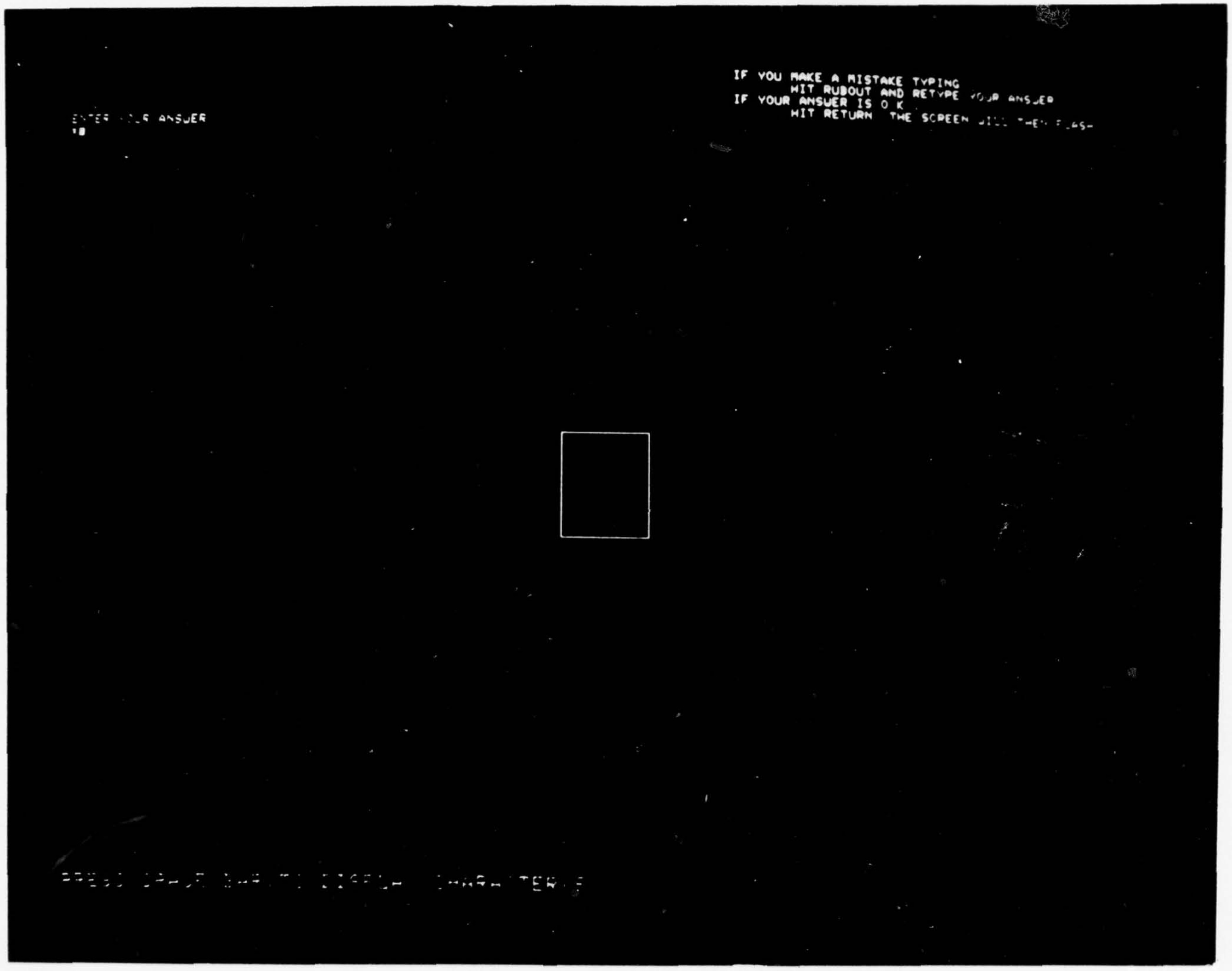

Figure 6. Subject's Response Instructions

press the button to display an alphanumeric character. As soon as the button was depressed, one alphanumeric character appeared in the fixation box (see Figure 5). As soon as the subject recognized the character, he/she pressed the button again. The character was then removed from the display, and any phosphor afterimage was removed by "star-dusting" the display (illuminating many random points) within the fixation box (Ripley, 1975).

The subject's response time was recorded by the computer. Response time was defined as the elapsed time from the moment when the character was first displayed until the subject pressed the button to indicate recognition of the character. It was calculated and recorded using the internal real-time clock of the computer. The subject was then asked to press the console key of the alphanumeric character that was just displayed (see Figure 6). This character was then displayed to the subject (in a defocused mode so that the character did not have the same distinct features as that shown to the subject), and the subject was asked by the computer to verify that he/she had pressed the correct console key. This procedure allowed the subject an opportunity to correct any console key errors, thus separating any motor or keying error from his/her perception of the alphanumeric character. At viewing distances other than 0.61 m, the investigator pressed the alphanumeric character console key at the verbal command of the subject. (At viewing distances greater than 0.61 m, the subject was not able to reach the console keyboard.) The subject's final response was entered into the computer by pressing the "RETURN" console key, which "flashed" the CRT display and caused the computer to record both the alphanumeric character that was presented to the subject and the alphanumeric character that the subject chose as a response. If the subject did not respond to the character within 10 s, the computer automatically removed the character from the display and recorded a blank as the subject's response. The computer then displayed the fixation box to begin the next trial.

Accuracy was defined as the percent correct, or the number of correct recognitions per experimental condition divided by the total number of presentations made at that experimental conditions.

To obtain tachistoscopic recognition data, the subject was seated in front of the CRT display at the normal viewing distance of 0.61 m. The method of character presentation and subject response was the same as that described above, except that no provision was made to measure the subject's response time.

Tachistoscopic recognition accuracy was defined in exactly the same way as recognition accuracy.

The data collected under the recognition response measure were used to determine the threshold visibility values as will be described subsequently.

Results

Accuracy. Initial statistical analyses of the accuracy data were performed using the analysis of variance as summarized in Table 5. Character size, luminance, and subjects were treated as random variables, while viewing distance was considered a fixed-effect variable. The expected mean square terms required the use of quasi-F ratios to keep the F-tests from being biased (Myers, 1973).

TABLE 5. Analysis of Variance Summary for Accuracy

Source of Variance	*df*	*MS*	*F*	*p*
Character Size (C)	3	670.23	47.04[a]	.001
Luminance (L)	2	180.24	14.10[a]	.005
Distance (D)	6	109.44	8.24[a]	.001
Subjects (S)	5	979.71	---	---
$C \times L$	6	8.82	3.45	.01
$C \times D$	18	75.98	16.36[a]	.001
$L \times D$	12	21.80	5.03[a]	.001
$C \times S$	15	7.92	---	---
$L \times S$	10	6.46	---	---
$D \times S$	30	22.77	---	---
$C \times L \times D$	36	3.78	2.05	.01
$C \times D \times S$	90	2.49	---	---
$C \times L \times S$	30	2.71	---	---
$L \times D \times S$	60	2.40	---	---
$C \times L \times D \times S$	180	1.85	---	---
Total	503			

[a]Quasi-*F* ratios, see text.

All of the main effects, first-order interactions, and second-order interactions were significant. Simple effects were analyzed, and the Newman-Keuls comparison statistic was used to evaluate further the design-related significant main effects and simple effects within significant interactions in Table 6. These analyses are summarized in Table 6. Figures 7 through 15 illustrate these significant sources of variation.

Generally, as character size increased, accuracy improved, with the greatest and only significant step improvement between 3.05 and 4.79 mm (Figure 7). This improvement with increasing size was more pronounced at 80 than at 27 cd/m^2, and greater at 27 than at 8 cd/m^2, as shown in Figure 8. Further, as viewing distance increased, performance at the lower C sizes (2.64 and 3.05) fell off more sharply than it did for 4.79 and 5.44 mm (Figure 9), and this difference in size over distance was greater for lower luminances (Figures 10-12).

The overall effect of increasing luminance is to improve accuracy (Figure 13); although this effect is relatively small, it is greater for the smaller sizes (Figure 8) and larger viewing distances (Figure 14).

Response time. Response times were also evaluated by the analysis of variance, summarized in Table 7. The C, L, and D main effects and the $C \times D$ interaction were found to be significant. Simple effects within the $C \times D$ interaction were then analyzed, and Newman-Keuls comparisons were made for design-related main effects and significant simple effects; these analyses are summarized in Table 8. Figures 15 through 18 provide additional information as to the nature of these significant sources of variation.

Response time decreases with increases in character size (Figure 15) and luminance (Figure 16). As with the accuracy measure, the greatest

TABLE 6. Summary of Significant Sources of Variance for Recognition Accuracy

Source of Variance[a]	Simple or Main Effect F	p	Individual Comparisons[b]
C	47.04	<.001	$\underline{C_1\ C_2}\ \underline{C_3\ C_4}$
L	14.10	<.005	$L_1\ \underline{L_2\ L_3}$
L @ C_2	6.60	<.005	$L_1\ \underline{L_2\ L_3}$
C @ L_1	11.23	<.001	$\underline{C_1\ C_2}\ \underline{C_3\ C_4}$
C @ L_2	11.78	<.001	$C_1\ C_2\ \underline{C_3\ C_4}$
C @ L_3	10.41	<.001	$C_1\ C_2\ C_3\ C_4$[c]
C @ D_4	6.26	<.005	$C_1\ C_2\ \underline{C_3\ C_4}$[d]
C @ D_5	17.09	<.001	$C_1\ C_2\ \underline{C_3\ C_4}$
C @ D_6	29.20	<.001	$C_1\ C_2\ \underline{C_3\ C_4}$[e]
C @ D_7	26.93	<.001	$\underline{C_1\ C_2}\ C_3\ C_4$
L @ D_5	4.52	<.025	$L_1\ \underline{L_2\ L_3}$
L @ D_6	5.26	<.025	$L_1\ \underline{L_2\ L_3}$
L @ D_7	6.50	<.025	$L_1\ \underline{L_2\ L_3}$

[a]No comparisons were made for the D effect simply because this variable has no design significance by itself.

[b]The variables not underlined are all significantly different from one another at the 0.01 level unless otherwise noted.

[c]C_3 significant from C_4 at 0.05 level.

[d]C_1 significant from C_2 at 0.05 level.

[e]C_1 significant from C_2 at 0.05 level.

TABLE 6--*Continued*

Source of Variance	Simple or Main Effect F	p	Individual Comparisons[b]
$C \times D_3$ @ L_1	4.60	<.005	$\underline{C_1\ C_2}\ C_3\ C_4$
$C \times D_4$ @ L_1	29.30	<.001	$\underline{C_1\ C_2}\ \underline{C_3\ C_4}$
$C \times D_5$ @ L_1	78.74	<.001	$\underline{C_1\ C_2}\ \underline{C_3\ C_4}$
$C \times D_6$ @ L_1	93.99	<.001	$\underline{C_1\ C_2}\ C_3\ C_4$
$C \times D_7$ @ L_1	59.45	<.001	$\underline{C_1\ C_2}\ C_3\ C_4$
$C \times D_3$ @ L_2	3.99	<.01	$\underline{C_1\ C_2}\ \underline{C_3\ C_4}$[f]
$C \times D_4$ @ L_2	12.60	<.001	$C_1\ \underline{C_2\ C_3\ C_4}$
$C \times D_5$ @ L_2	30.67	<.001	$C_1\ C_2\ \underline{C_3\ C_4}$
$C \times D_6$ @ L_2	75.58	<.001	$C_1\ C_2\ \underline{C_3\ C_4}$[g]
$C \times D_7$ @ L_2	72.45	<.001	$\underline{C_1\ C_2}\ C_3\ C_4$
$C \times D_4$ @ L_3	15.48	<.001	$C_1\ \underline{C_2\ C_3\ C_4}$
$C \times D_5$ @ L_3	32.79	<.001	$C_1\ C_2\ \underline{C_3\ C_4}$
$C \times D_6$ @ L_3	56.69	<.001	$\underline{C_1\ C_2}\ C_3\ C_4$
$C \times D_7$ @ L_3	73.75	<.001	$C_1\ C_2\ C_3\ C_4$[h]

[b]The variables not underlined are all significantly different from one another at the 0.01 level unless otherwise noted.

[f]C_1 and C_2 significant from C_3 and C_4 at approximately 0.05 level.

[g]C_1 significant from C_2 at 0.05 level.

[h]C_3 significant from C_4 at 0.05 level.

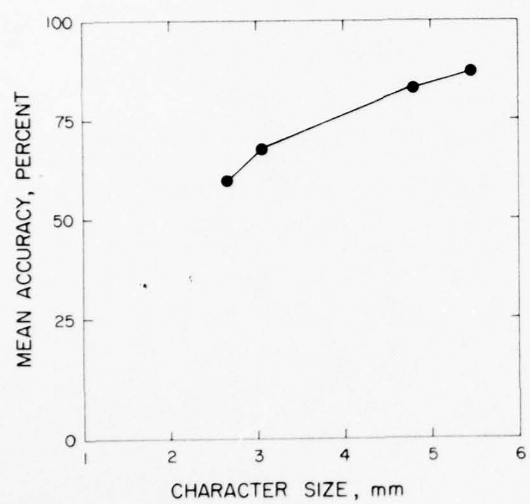

Figure 7. Effect of Character Size upon Accuracy

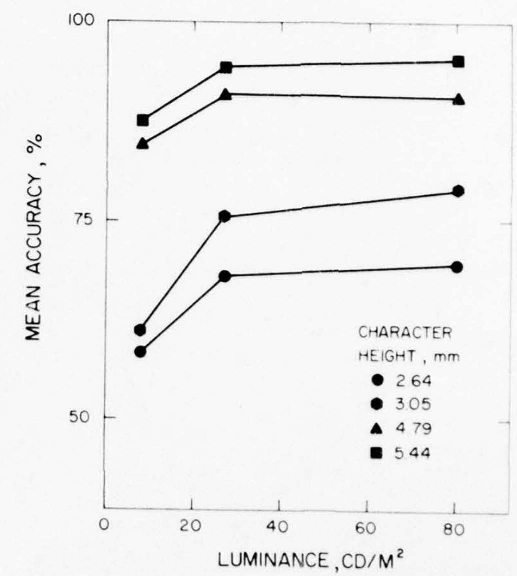

Figure 8. Effect of Character Size by Luminance Interaction upon Accuracy

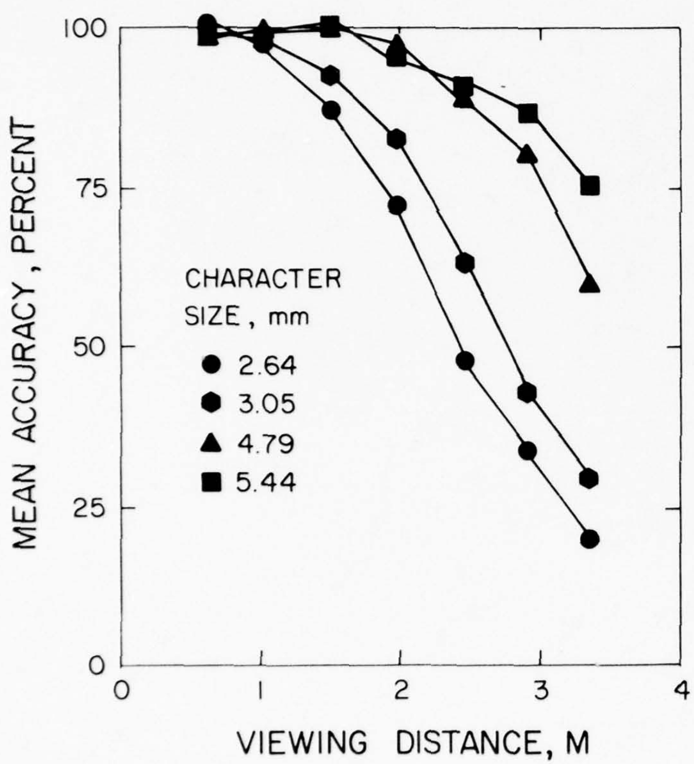

Figure 9. Effect of Character Size upon Accuracy at Various Viewing Distances

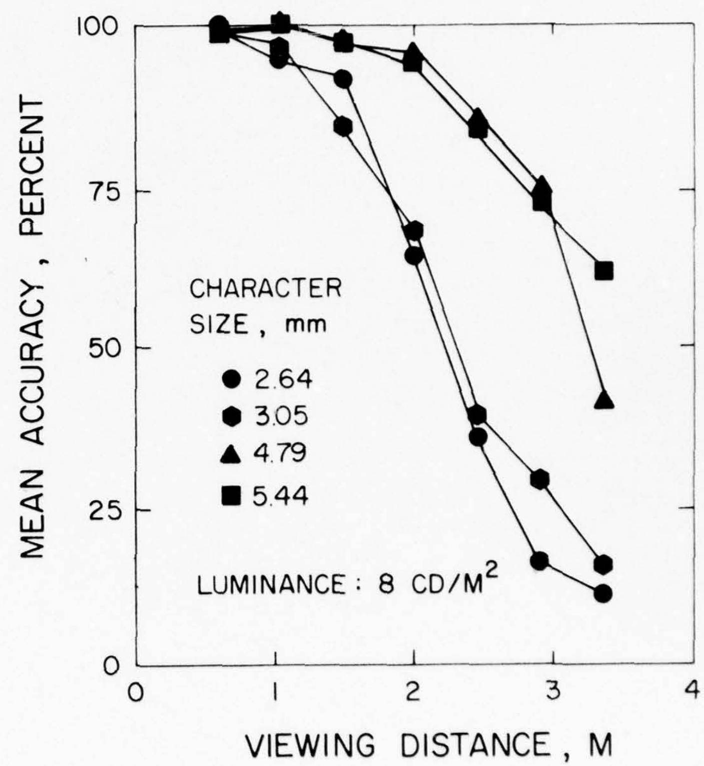

Figure 10. Interaction of Character Size by Distance at 8 cd/m^2

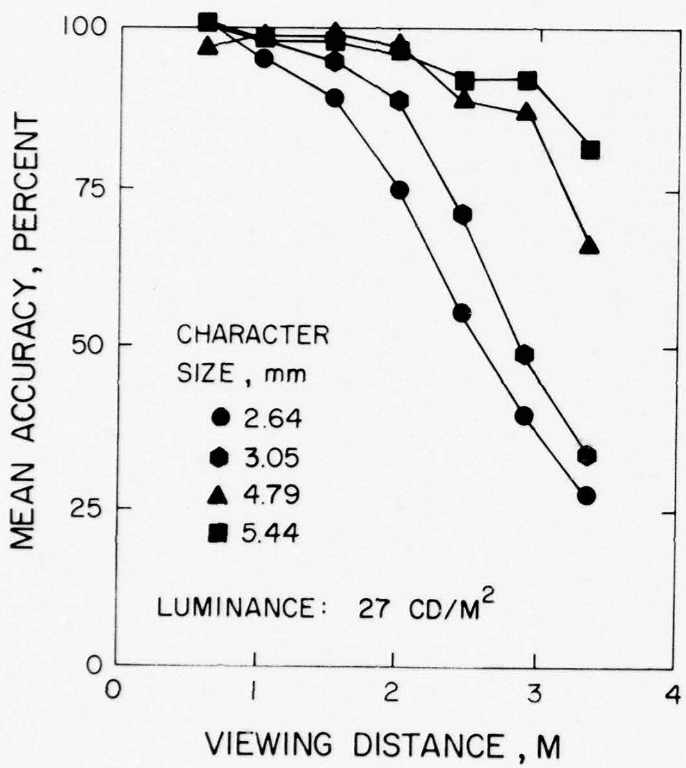

Figure 11. Interaction of Character Size by Distance at 27 cd/m^2

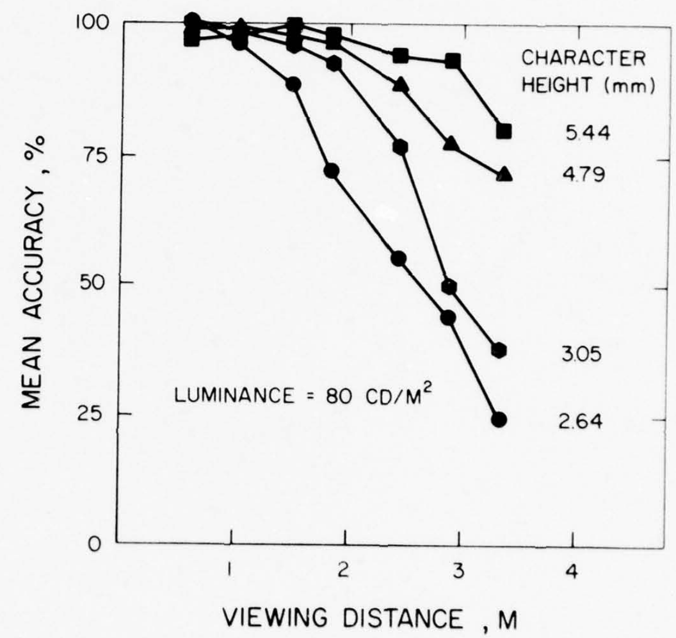

Figure 12. Interaction of Character Size by Distance at 80 cd/m^2

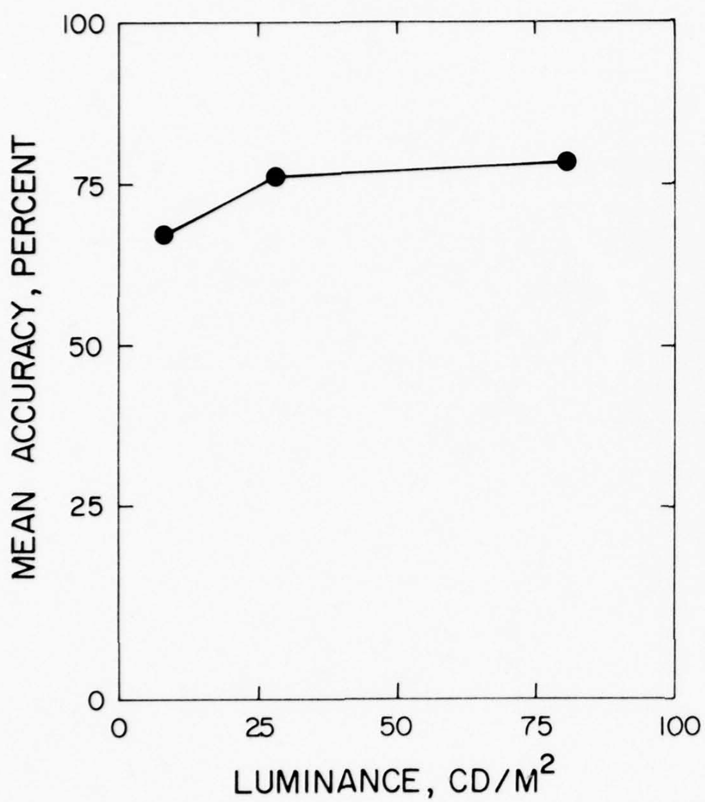

Figure 13. Effect of Luminance upon Accuracy

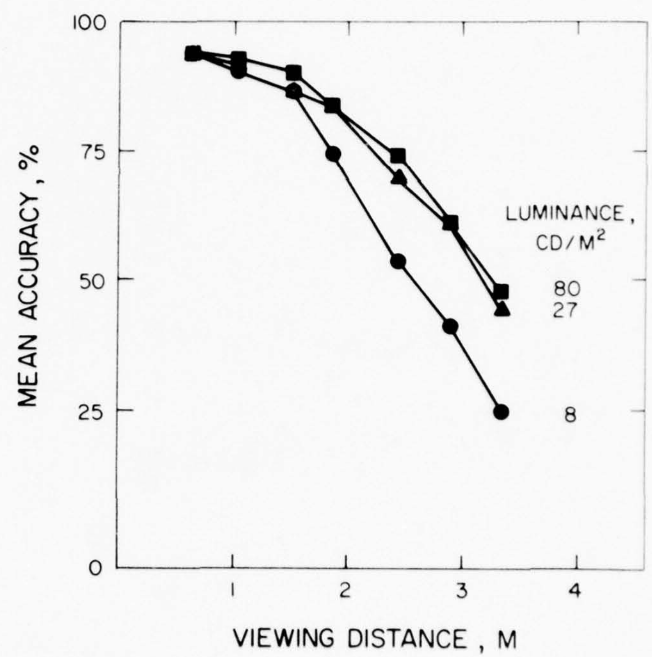

Figure 14. Effect of Luminance by Viewing Distance Interaction upon Accuracy

TABLE 7. Analysis of Variance Summary for Response Times

Source of Variance	*df*	*MS*	*F*	*p*
Character Size (C)	3	14977.217	102.25[a]	.001
Luminance (L)	2	5128.37	96.83[a]	.10
Distance (D)	6	28683.47	9.77[a]	.001
Subjects (S)	5	11739.69	---	---
$C \times L$	6	101.68	0.13	NS
$C \times D$	18	1008.55	4.94[a]	.005
$L \times D$	12	431.55	1.26[a]	NS
$C \times S$	15	851.53	---	---
$L \times S$	10	758.01	---	---
$D \times S$	30	1629.36	---	---
$C \times L \times D$	36	266.61	0.98	NS
$C \times L \times S$	30	806.72	---	---
$C \times S \times D$	90	209.62	---	---
$C \times L \times D \times S$	180	272.06	---	---

[a]Quasi-*F*s.

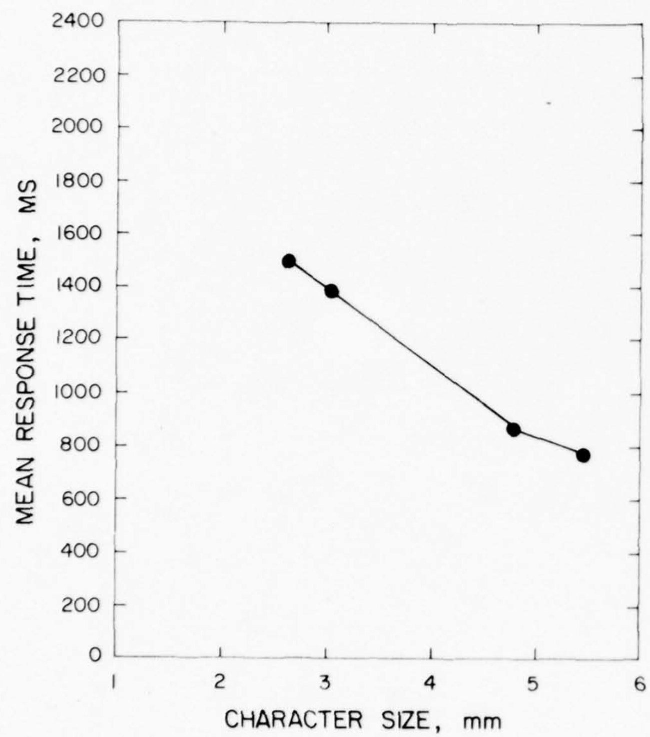

Figure 15. Effect of Character Size upon Response Time

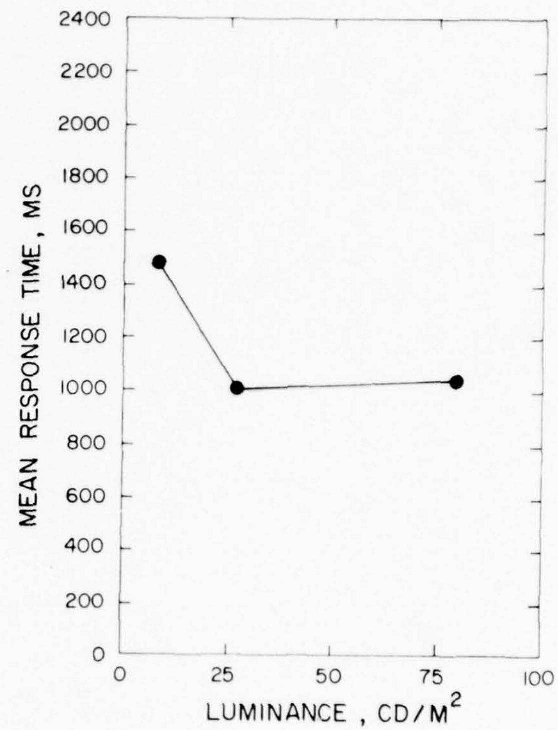

Figure 16. Effect of Luminance upon Response Time

improvements are obtained between 3.05 and 4.79 mm for character size, and between 8 and 27 cd/m^2 for luminance increases. As expected, increases in viewing distance cause increases in response time (Figure 17), with the effect of character size becoming greater at larger viewing distances (Figure 18).

TABLE 8. Summary of Significant Sources of Variance for Response Times

Source of Variance[a]	*Simple or Main Effect* *F*	*p*	*Individual Comparisons*[b]
C	102.25	<.001	C_1 C_2 C_3 C_4 [c]
L	96.83	<.10	L_1 L_2 L_3 [d]
C @ D_4	6.74	<.005	C_1 C_2 C_3 C_4
C @ D_5	12.43	<.001	C_1 C_2 C_3 C_4
C @ D_6	6.65	<.005	C_1 C_2 C_3 C_4
C @ D_7	5.99	<.01	C_1 C_2 C_3 C_4

[a]No comparisons were made for the D effect simply because this variable has no hardware design significance by itself.

[b]The variables not underlined are all significantly different from each other at the 0.01 level unless otherwise noted.

[c]C_3 significant from C_4 at 0.05 level.

[d]L_1 significant from L_2 and L_3 at 0.05 level.

Tachistoscopic recognition. Tachistoscopic recognition data were also analyzed by the analyses of variance shown in Table 9 with the appropriate quasi-F ratios. At 16.67 and 50 ms exposure times, only the $C \times L$ interaction was found to be significant (Figures 19 and 20). No significant effects were found at the 33.33 ms exposure time.

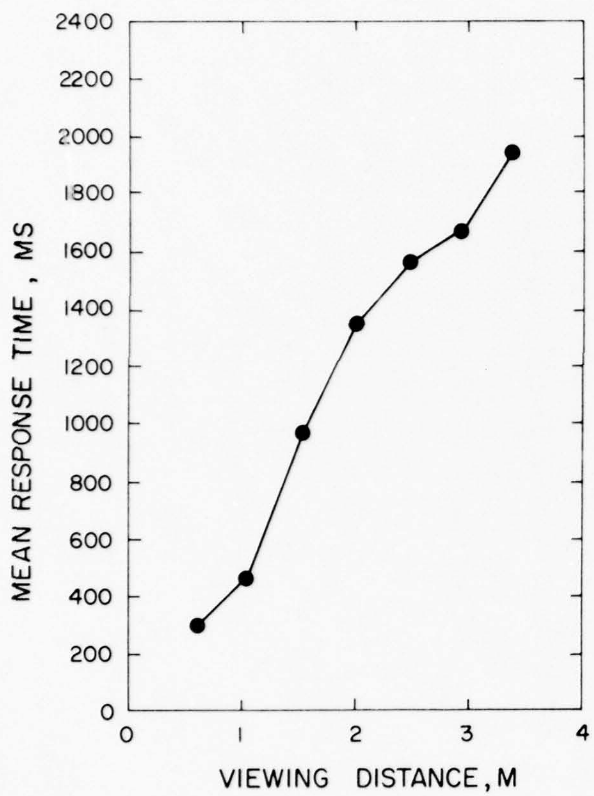

Figure 17. Effect of Viewing Distance upon Response Time

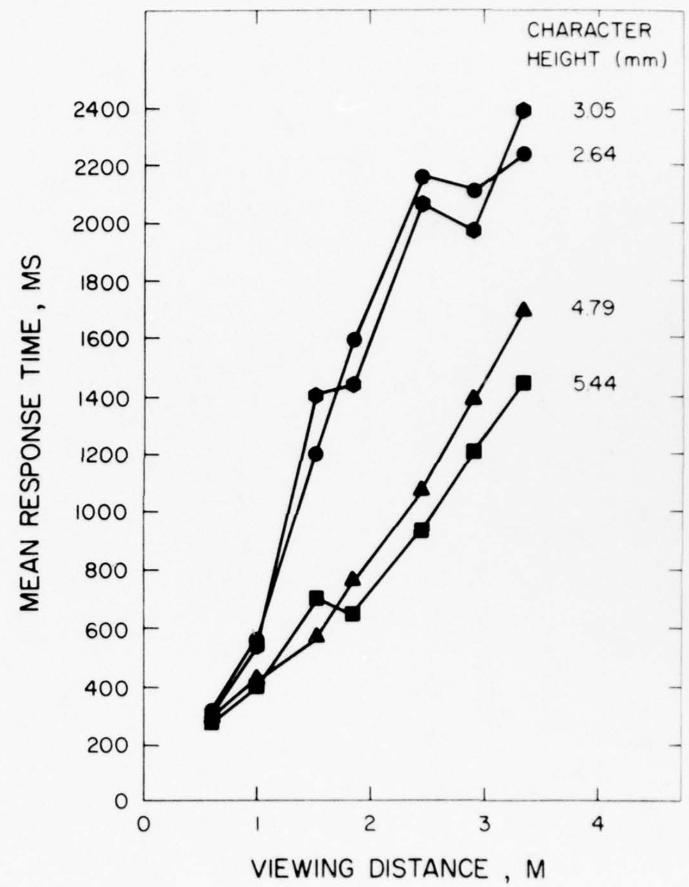

Figure 18. Effect of Viewing Distance by Character Size Interaction upon Response Time

TABLE 9. Analysis of Variance Summary for Tachistoscopic Recognition Accuracy

Exposure Time (ms)	*Source of Variance*	*df*	*MS*	*F*	*p*
	Character Size (C)	3	6.02	2.41[a]	NS
	Luminance (L)	2	11.38	4.93[a]	NS
	Subjects (S)	5	2.77	---	---
16.67	$C \times L$	6	2.39	4.15	<.005
	$L \times S$	10	0.49	---	---
	$C \times S$	15	0.69	---	---
	$C \times L \times S$	30	0.58	---	---
	Character Size (C)	3	0.57	9.81[a]	NS
	Luminance (L)	2	0.18	7.54[a]	NS
	Subjects (S)	5	0.18	---	---
33.33	$C \times L$	6	0.13	0.40	NS
	$L \times S$	10	0.21	---	---
	$C \times S$	15	0.25	---	---
	$C \times L \times S$	30	0.31	---	---
	Character Size (C)	3	0.44	0.96[a]	NS
	Luminance (L)	2	0.50	0.99[a]	
	Subjects (S)	5	0.10	---	---
50.00	$C \times L$	6	0.45	3.20	<.025
	$L \times S$	10	0.20	---	---
	$C \times S$	15	0.16	---	---
	$C \times L \times S$	30	0.14	---	---

[a]Quasi-*F*s.

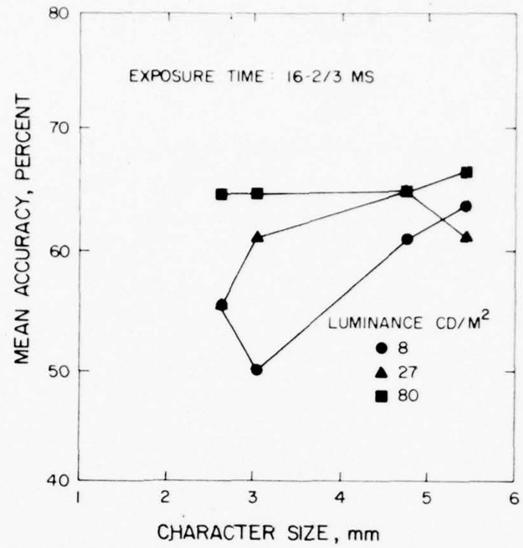

Figure 19. Effect of Character Size by Luminance Interaction at 16.67 ms Exposure Time

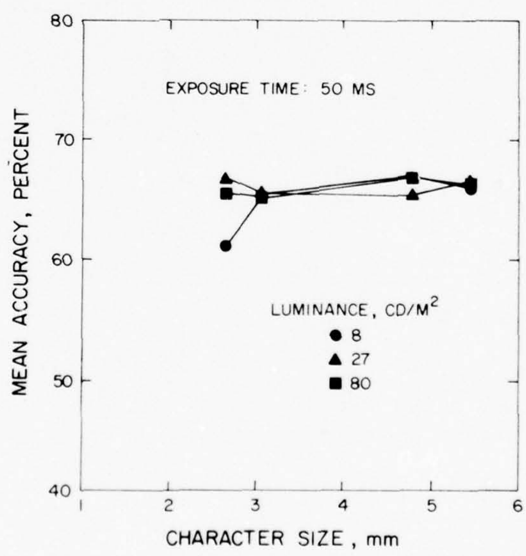

Figure 20. Effect of Character Size by Luminance Interaction at 50 ms Exposure Time

Simple effects were then analyzed and Newman-Keuls multiple comparisons were used to evaluate the means, as summarized in Table 10.

TABLE 10. Summary of Significant Sources of Variance for Tachistoscopic Recognition Accuracy

Exposure Time (ms)	*Source of Variance*	*Simple or Main Effect* *F*	*p*	*Individual Comparisons*[a]
33.33	L @ C_1	8.76	<.005	$L_1\ L_2\ L_3$
	L @ C_2	20.03	<.001	$L_1\ \underline{L_2\ L_3}$
50.00	L @ C_1	5.48	<.01	$L_1\ \underline{L_2\ L_3}$[b]

[a]The variables not underlined are all significantly different from one another at the 0.01 level unless otherwise noted.

[b]L_1 significant from L_2 and L_3 at 0.05 level.

For the small character sizes, increases in luminance typically improved performance (Figures 19 and 20), with the difference decreasing as character size increased. This interaction effect was inconsistent, however, as illustrated by the nonsignificant effect at 33.33 ms.

Visibility threshold. The psychophysical Method of Constant Stimuli (Guilford, 1954) was used to develop 50% and 85% visibility thresholds for each of the 12 $C \times L$ combinations. Traditionally, threshold measures are made at the 50% level. However, 85% accuracy level is often used as an acceptable criterion for alphanumeric display visibility (Shurtleff, 1967); therefore, 85% values were also determined.

Accuracy (in percent correct) was plotted against the seven viewing distances; these curves were then transformed into linear plots by converting the percent scores to standard (z) scores. Percent scores of 100 were deleted from this analysis to avoid extreme-score bias. A least-squres regression was performed on these transformed data and the least-squares, best-fit was determined. The 50% and 85% threshold viewing distances were obtained from the regression equation for each $C \times L$ combination.

The 50% and 85% visibility threshold distances are summarized in Figures 21 and 22, respectively.

Initial statistical analyses of the 50% and 85% threshold visibility data were performed by using analyses of variance (Tables 11 and 12, respectively). The Newman-Keuls comparison statistic was used to evaluate further the design-related significant main effects, as also indicated in Tables 11 and 12.

TABLE 11. Analysis of Variance Summary for 50% Threshold Visibility

Source of Variance	*df*	*MS*	*F*	*p*	*Individual Comparisons*[a]
Character Size (C)	3	4960.66	17.40	<.005	$C_1\ C_2\ C_3\ C_4$
Luminance (L)	2	1746.33	6.13	<.05	$\underline{L_1\ L_2\ L_3}$[b]
$C \times L$	6	285.14	---	---	

[a]The variables not underlined are all significantly different from one another at the 0.05 level unless otherwise noted.

[b]Probable cause of non-significance is the small number of data points.

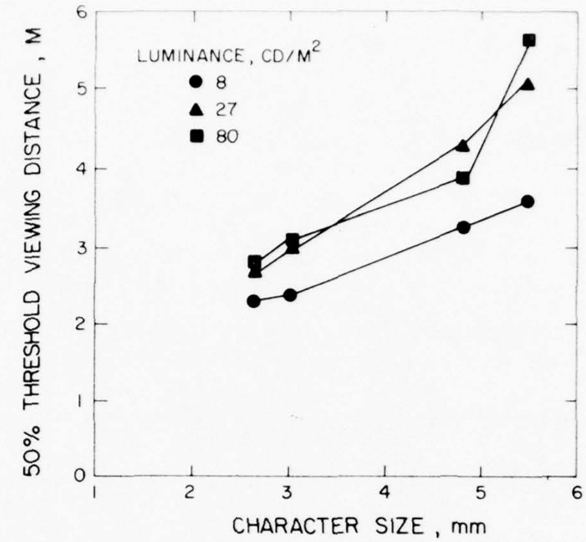

Figure 21. 50% Threshold Visibility Distances

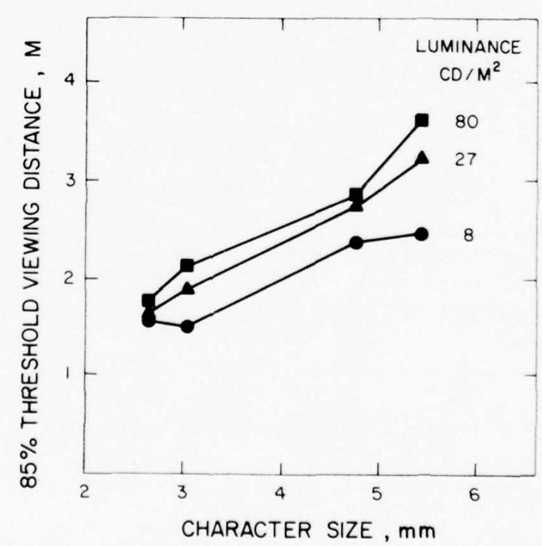

Figure 22. 85% Threshold Visibility Distances

TABLE 12. Analysis of Variance Summary for 85% Threshold Visibility

Source of Variance	*df*	*MS*	*F*	*p*	*Individual Comparisons*[a]
Character Size (C)	3	2332.98	33.09	<.001	$\underline{C_1\ C_2}\ \underline{C_3\ C_4}$[b]
Luminance (L)	2	617.33	7.76	<.025	$\underline{L_1\ L_2\ L_3}$[c]
$C \times L$	6	70.49	---	---	

[a]The variables not underlined are all significantly different from one another at the 0.05 level unless otherwise noted.

[b]C_1 significant from C_4 at 0.01 level.

[c]Probable cause of non-significance is the small number of data points.

For both the 50% and 85% thresholds as character size increases the threshold viewing distance also increases. For the 50% threshold measure, 2.64 and 3.05 mm are significantly different from 5.44 mm. For the 85% threshold data, 2.64 and 3.05 mm are significantly different from both 4.79 and 5.44 mm. Thus, the general trend is that increases in threshold (both 50% and 85%) viewing distance are obtained with increasing character size. However, each size step increase does not produce a statistically significant increase in threshold distance, largely due to the low statistical power (small *df*).

While increases in luminance have an overall increasing effect upon these thresholds, the Newman-Keuls comparison statistic failed to show any individual luminance level differences. This was probably caused also by the small number of data points (or *df*) for each cell.

Comparison of response measures. An overall summary of the sensitivity of the different operator response measures to the different display variables is shown in Table 13. Recognition accuracy showed the most sensitivity. Response times were less sensitive to combinations of C and L, but they still provided considerable information about the display parameters.

Tachistoscopic recognition was relatively insensitive to the display variables, probably due to the small 0.61 m viewing distance combined with the relatively long exposure durations. The tachistoscopic measure would probably have been more sensitive if the exposure times had been shorter. This, however, was not possible with the existing equipment.

The threshold visibility measure was developed from the accuracy data and is not really comparable, in statistical sensitivity terms, to accuracy or tachistoscopic recognition. However, Figure 22 shows that the threshold visibility data essentially agree with the recognition data. In fact, correlations among the 12 $C \times L$ means for the several response measures are quite high, as shown in Table 14.

Discussion

Accuracy maintains a consistent correlation with the other measures. Response time is not appreciably different from recognition accuracy in terms of correlation consistency. However, in terms of experimental design and data collection, it is much easier to obtain accuracy measures than to obtain response time measures.

The intercorrelations pertaining to the tachistoscopic recognition again indicate that, as a response measure, it is not as sensitive a linear measure of legibility as are the other response measures.

TABLE 13. Sensitivity Comparisons of Operator Response Measures

	Operator Response Measures					
			Tachistoscopic Recognition (ms)			(85%) Visibility
Display Variables	*Accuracy*	*Response Time*	*16.67*	*33.33*	*50.00*	*Threshold*
C	$p<.001$	$p<.001$	NS[a]	NS[a]	NS[a]	$p<.001$
L	$p<.005$	$p<.10$	NS[a]	NS[a]	NS[a]	$p<.025$
D	$p<.001$	$p<.001$	NM[b]	NM[b]	NM[b]	NM[b]
$C \times L$	$p<.01$	NS[a]	$p<.005$	NS[a]	$p<.025$	NM[b]
$C \times D$	$p<.001$	$p<.005$	NM[b]	NM[b]	NM[b]	NM[b]
$L \times D$	$p<.001$	NS[a]	NM[b]	NM[b]	NM[b]	NM[b]
$C \times L \times D$	$p<.01$	NS[a]	NM[b]	NM[b]	NM[b]	NM[b]

[a]Not significant (NS). [b]Not measured (NM).

TABLE 14. Product-Moment Intercorrelations Among Response Measures for the 12 $C \times L$ Means

	Operator Response Measures				
			Tachistoscopic Recognition Exposure Time (ms)		
	Accuracy	*Response Time*	*16.67*	*33.33*	*50.00*
Response Time	-0.97	---			
Tachistoscopic Recognition (16.67 ms)	0.78	-0.72	---		
Tachistoscopic Recognition (33.33 ms)	0.83	-0.64	0.62	---	
Tachistoscopic Recognition (50.00 ms)	0.60	-0.60	0.38	0.53	---
85% Threshold Visibility	0.94	-0.96	0.69	0.78	0.48

Threshold visibility measures remain consistent with accuracy and response time, but they require more data points (data at each viewing distance) to obtain a measure of observer performance as used herein. Thus, the recognition accuracy measure seems best overall due to its ease of data collection and its high consistency and sensitivity across all experimental variables.

Besides being statistically significant or sensitive, a response measure should also demonstrate practical significance. In other words, the response measure should account for a substantial amount of the practical variation found in the experiment. Intra-class correlations (accountable variation) were measured on the different response measures and are shown for the main effects in Table 15.

TABLE 15. Percent Accountable Variation (Intra-Class Correlation)

	Operator Response Measures					
			Tachistoscopic Recognition Exposure Time (ms)			85% Threshold
Source of Variance	*Accuracy*	*Response Time*	*16.67*	*33.33*	*50.00*	*Visibility*
C	14.33	5.79	29.67	4.50	9.31	76.77
L	3.04	1.49	14.81	1.16	7.80	16.48
D	40.06	20.91	---	---	---	---
S	3.80	11.61	9.79	3.48	4.80	---

Across all the response measures, character size accounts for a much larger percent variation than does luminance. Character size, under the recognition accuracy response measure, provided a maximum of 4.7 times more accountable variation than did luminance.

Of course, the effects of viewing distance are also shown to account for large percentages of the practical variation. Over 40% of the variation in accuracy is attributable to viewing distance, while over 20% can be attributed to viewing distances for response time.

It should also be remembered that the response measure selected should be meaningful to the system criteria (Chapanis, 1971). Cornog and Rose (1967) found that over the years investigators have used an astonishing variety of response measures in studying the problem of evaluating the legibility of type. However, to be meaningful, the response measure must have some relation to the task the operator performs in the real-life system. For this reason alone, the legibility of alphanumeric characters would probably be better measured by a recognition accuracy or threshold visibility task than by any other response measure. If the operator cannot accurately read a given symbol, system errors are likely to occur. Speed in the absence of accuracy is of doubtful merit. There are very few, if any, visual displays that are actually operated in a mode of tachistoscopic presentation.

Display Parameters

Character size, luminance, and viewing distance proved to have consistent and significant effects upon the legibility of dot-matrix alphanumeric characters at viewing distances larger than 1.5 m. To overcome the adverse effects of small character sizes, luminance should be increased and, conversely, to overcome the adverse effects of low luminance levels, character size or angular subtense should be increased.

Character size. Shurtleff (1967) and Howell and Kraft (1959) have recommended that alphanumeric characters should subtend at least 12 min of visual angle at the eye in order to provide adequate legibility, where adequate legibility is defined as 85% accuracy. Figure 7 shows that the improvement in legibility (accuracy) is insignificant for character sizes large than 4.79 mm, whereas Figure 9 indicates that improvement in legibility is insignificant for viewing distances less than 1.5 m. These results thus establish the legibility cutoff point as a character size 4.79 mm at a viewing distance of 1.5 mm. At these values the character subtends 10.80 min of visual angle at the eye (Table 3). The results of this experiment are thus quite consistent with these established guidelines.

Luminance. According to Gould (1968), any display luminance of about 68 cd/m^2 is probably adequate, assuming that the ambient illuminance is such that sufficient modulation is maintained between the displayed characters and their background. The results of this experiment are also relatively consistent with this recommendation. Accuracy decreased and response time increased significantly when the mean character (display) luminance was decreased from 27 to 8 cd/m^2. Accuracy and response time did not improve significantly when luminance was increased beyond 27 cd/m^2.

Ambient illuminance was negligible and luminance modulation for the three different levels of luminance was 0.41, 0.78, and 0.92 (contrast ratios of 2.4:1, 7.98:1, and 23.8:1), respectively. These results are consistent with those of Howell and Kraft (1959), who have recommended a desirable luminance modulation of 0.94 and an acceptable modulation of 0.88 for relatively small character sizes (less than 16 min of visual angle).

Care should be taken in establishing the luminance levels based upon the tachistoscopic presentation data. It is possible that the pulse width, or actual "on" time, of the electron beam will vary for different luminance levels depending on the threshold characteristics of the display phosphor, i.e., differential rise and decay times of threshold viewing luminances as a function of z-axis modulation. This possible confounding of "true" presentation time is significant due to the fact that the exposure times used in this study are within the range of times over which the visual system is a virtually perfect temporal integrator (Blondel and Rey, 1911).

Viewing distance. At viewing distances smaller than 1.5 m, the levels of luminance and character size used in this study did not have significant effects upon performance. When a display is to have multiple operators and, of necessity, the viewing distance must be larger than 1.5 m, the choice of the display becomes dependent on its capabilities to display larger character sizes at higher luminance levels.

Conclusions from this Experiment

Recognition accuracy was found to be the operator response measure that is generally most sensitive to the display parameters of character size, luminance, and viewing distance, although other response measures showed considerable sensitivity and reliability.

Character size, character luminance, and viewing distance proved to have consistent and significant effects at viewing distances greater than 1.5 m. At lesser viewing distances, these parameters had little effect.

The results showed that by increasing luminance, response accuracy can generally be increased. To overcome the adverse effects of small character size, luminance should be increased and, conversely, to overcome the adverse effects of low luminance levels, character size should be increased.

Display modulation should be greater than 0.78 to obtain adequate legibility (85% accuracy), while characters should subtend at least 10.8 min of visual angle at the eye.

The results also indicate that there is no significant difference between the display requirements for these computer-generated dot-matrix characters *vs*. those for conventional CRT displays.

While it was shown that character size is a significant variable in achieving adequate legibility, further evaluation of character construction should provide even more useful guidelines for prototype designs. The evaluation of different dot sizes, inter-dot spacings, and dot shapes, studied in subsequent experiments, provide information as to exactly which character constituents are most important in legibility.

While character confusion was not of interest in this experiment, it was noted that subjects tended to confuse certain characters consistently. Evaluations of different font styles were subsequently performed to provide information to resolve this problem. It must be remembered that different character fonts should be compared and evaluated at each dot-matrix size and not generally averaged across dot-matrix sizes. The reason for this is that, as the matrix size gets larger, it becomes easier to duplicate the more difficult or elaborate font patterns.

III. OPTIMAL ELEMENT SIZE-SHAPE-SPACING COMBINATIONS FOR A 5 × 7 MATRIX

Introduction

Earlier discussions in this report have pointed out that the individual dot-matrix character has, inherently, resulted from design decisions regarding both matrix size and dot charactersitcs. Studies described later in this report address the question of optimal matrix size (e.g., 5 × 7, 7 × 9, 9 × 11, etc.). In the experiment reported in this section, attention was given to three design variables relevant to each dot of the dot matrix and the interaction of these variables with the ambient illuminance level.

The four variables, i.e., element size, element shape, inter-element spacing, and ambient illuminance, were studied to determine how they affect legibility and, more importantly, to derive some optimal combinations of these four variables. Due to the confusion surrounding the effects of these variables, a broad range of combinations was selected (54 combinations of the variables, total). Also, since different tasks may require disparate combinations of the variables for optimal observer performance, it was necessary to use three separate, but representative, observer tasks and to analyze each task's results independently of the other tasks. With the results of this study, it is hoped that industrial designers, for instance, can fabricate a dot-matrix visual display superior to displays of the past in terms of individual and contextual character legibility.

Font Selection

At the time this study was conducted, there was no demonstrated superior font for dot-matrix characters. VanderKolk, *et al.* (1975) concluded that legibility differences between dot-matrix fonts were minimal, so they chose the Lincoln/Mitre (L/M) font for their experiments due to its popularity as a stroke font. Maddox, Burnette, and Gutmann (1977) showed significant differences among three 5×7 fonts. They created two of the fonts; the third was the L/M font, as adapted by VanderKolk, *et al.* to dot-matrix displays. The greatest number of errors was obtained with the Lincoln/Mitre font; the best font led to 18% fewer errors than did the L/M. This shows that improvements are possible over the L/M for 5×7 dot-matrix applications. (See Section VI for details of the Maddox, *et al.* (1977) experiment.)

Though the three fonts can be ranked in order of total number of errors, any of the three fonts may have been best on one particular alphanumeric character. It is advantageous to further minimize total errors for a proposed alphanumeric font by picking the best font of the three for each alphanumeric character. This "composite font" (Figure 23) would theoretically have 46% fewer total errors than would the L/M and was used as an optimal 5×7 dot-matrix font during this experiment.

Method

Experimental design. The four fixed-effects variables--element size, interelement spacing, element shape, and ambient illuminance--were combined in a full factorial design (Figure 24). Three of these

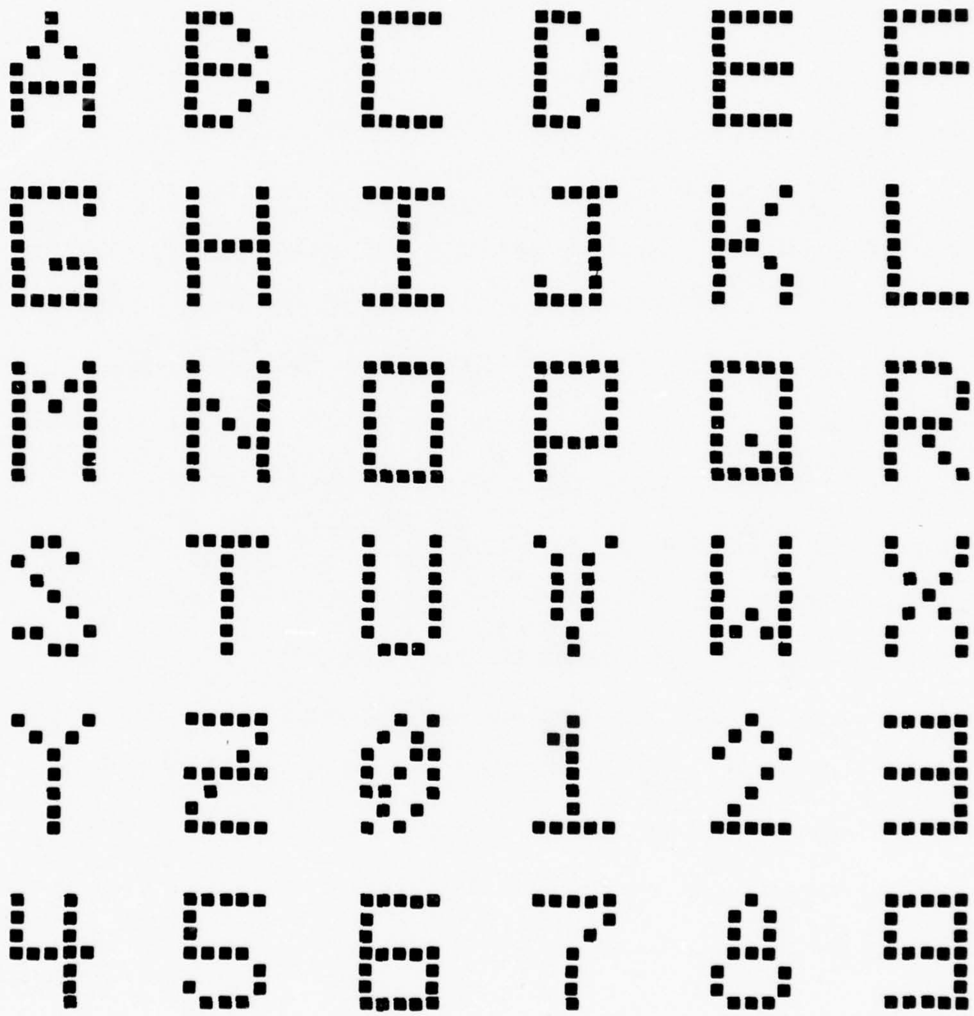

Figure 23. Composite 5 × 7 Font

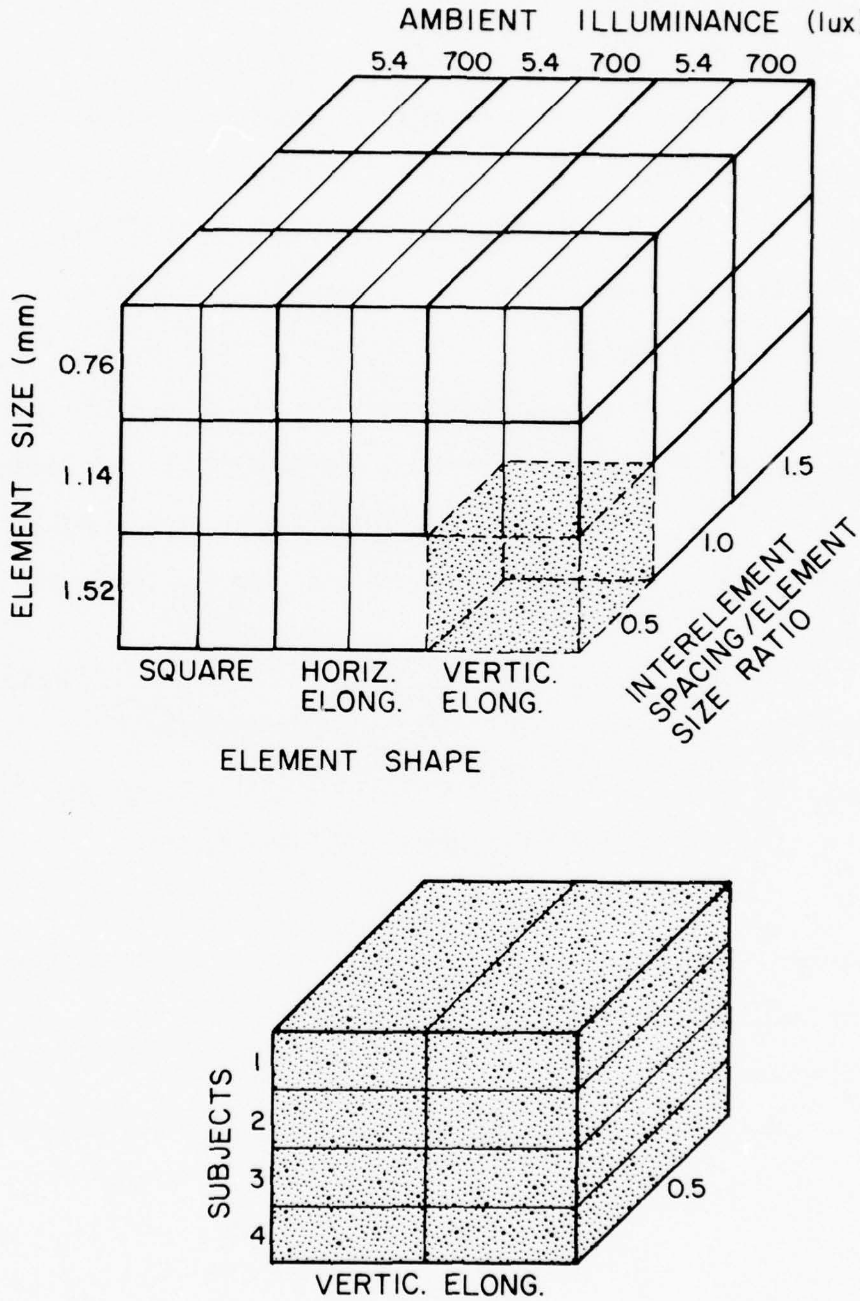

Figure 24. Experimental Design

variables--element size, element shape, and interelement spacing--were studied as between-subjects variables. There were three levels of each of these variables. Subjects were assigned randomly to treatment levels, with four subjects in each of the 27 cells. Each cell's conditions were repeated for each subject under both high and low ambient illuminance levels.

Three separate tasks were used and are described here. A counterbalanced procedure controlled order effects of the two types of search tasks, the ambient illuminance levels, and the two different forms of the reading test. There were three levels each of element shape, element size, and interelement spacing, and two levels of illuminance.

Element shape. Due to dot blooming and the general irregularity of each of the small points on the display, it is not possible to creat exact replicas of geometric shapes such as squares, circles, or rectangles. If enough of these points are combined, these shapes and orientations can be approximated closely, however.

For this experiment, squares and rectangles were simulated. The latter were divided into vertically and horizontally oriented rectangles, i.e., the longest dimension fell along the vertical or horizontal axes, respectively (Figure 25).

Element size. The three levels of element size were 0.76 mm, 1.14 mm, and 1.52 mm. These sizes were subjectively determined to present readily detectable differences in size (Figure 25).

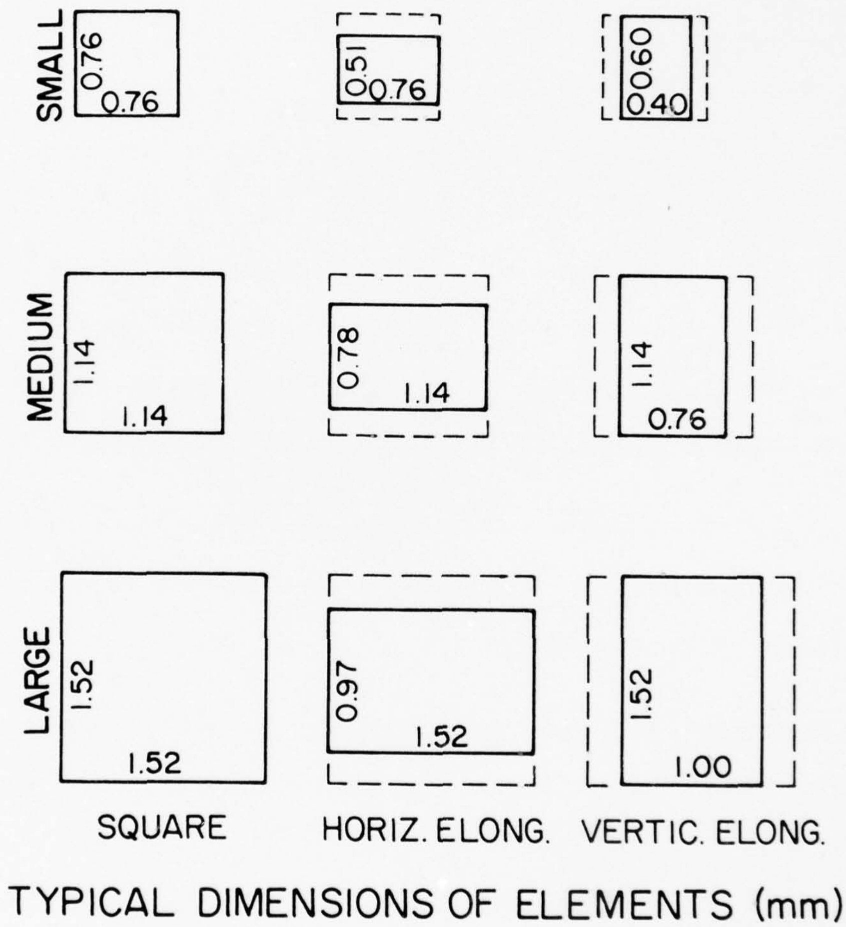

Figure 25. Element Size Dimensions

Interelement spacing. Three levels of spacing ratios were used so that the edge-to-edge space/element size ratios were 0.5, 1.0, and 1.5. There were nine size-space conditions as the actual spacing was different for each element size, but the spacing ratios were constant across element size. The rectangles were actually centered within a larger cell the size of the corresponding square. This minimized the total number of overall character size dimensions, while providing a simple method of setting the interelement spacing (Figures 25, 26; Table 16). The sizes and shapes of individual dots were obtained by combination of minipoints, or the smallest computer addressable point, as described in the previous section and illustrated in Figure 26. All of the characters exceeded 23 minutes of vertical subtense to minimize the effects of overall character size (Semple, *et al.*, 1971). Figures 27 and 28 illustrate two of the experimental conditions.

Ambient illuminance. As mentioned above, the two illuminance levels were a moderately subdued office level and a much more subdued level of approximately 700 and 5.4 lx, respectively.

Subjects. There were 108 college age subjects used in this research, 61 male and 47 female, randomly assigned to the experimental conditions. All subjects were screened for 20/25, or better, corrected visual acuity as well as normal phoria, color vision, and depth perception with an Orthorater vision tester. These tests were performed at near (0.33 m) and far (6.1 m) equivalent distances.

Dependent measures. There were three performance measures taken during the study to measure legibility of the characters created by the

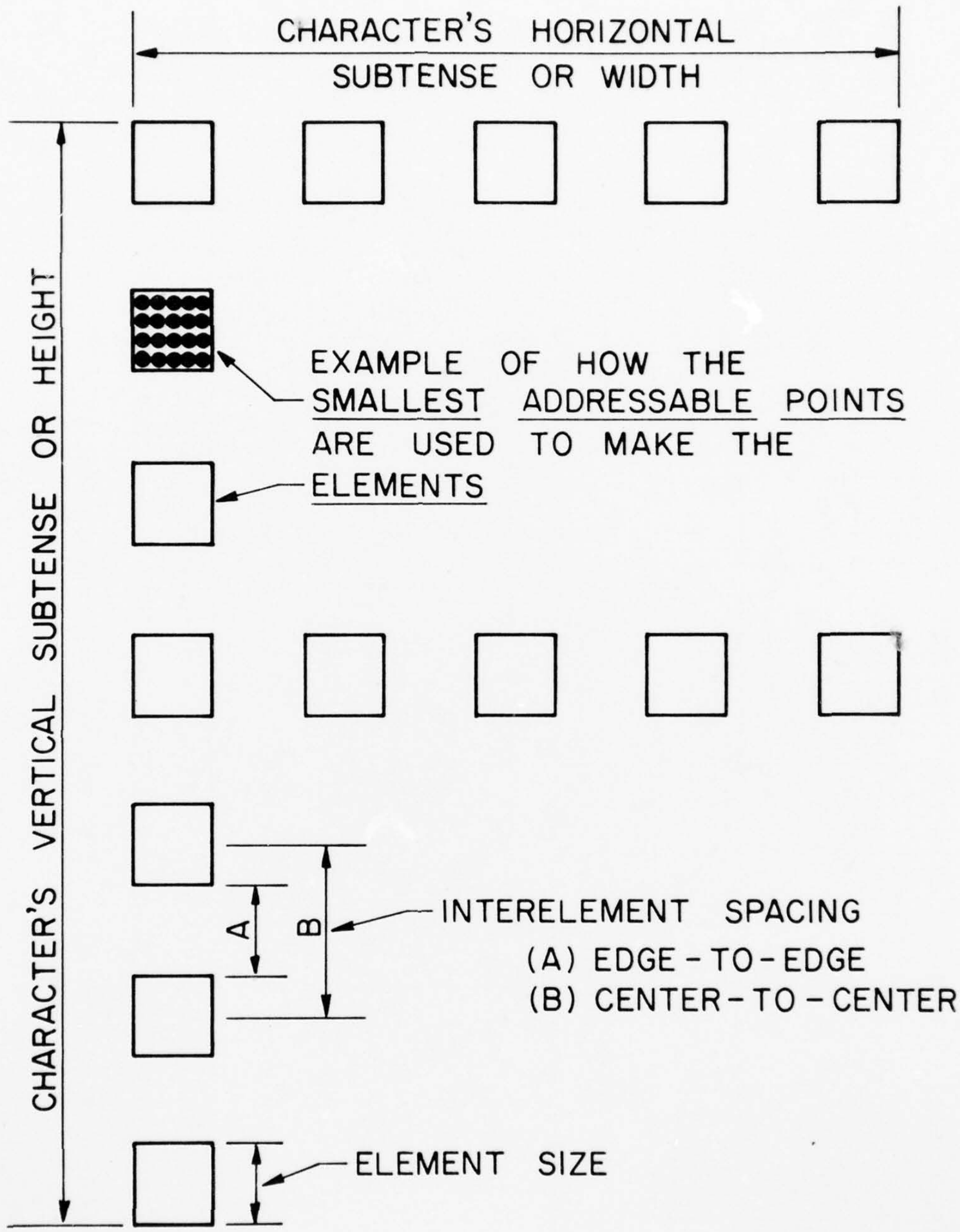

Figure 26. Character "F" and Its Development

TABLE 16. Edge-to-Edge Dimensions of Character Matrices

Element Size (mm)	Interelement Space/Size Ratio	Interelement Horizontal Space (mm)			Interelement Vertical Space (mm)			Character Size (mm)[b]	
		■	▬	▮[a]	■	▬	▮[a]	Width	Height
	0.5	0.38	0.38	0.74	0.38	0.63	0.54	5.32	7.60
0.76	1.0	0.76	0.76	1.12	0.76	1.01	0.92	6.84	9.88
	1.5	1.14	1.14	1.50	1.14	1.39	1.30	8.36	12.16
	0.5	0.57	0.57	0.95	0.57	0.93	0.57	7.98	11.40
1.14	1.0	1.14	1.14	1.52	1.14	1.50	1.14	10.26	14.82
	1.5	1.71	1.71	2.09	1.71	2.07	1.71	12.54	18.24
	0.5	0.76	0.76	1.28	0.76	1.31	0.76	10.64	15.20
1.52	1.0	1.52	1.52	2.04	1.52	2.07	1.52	13.68	19.76
	1.5	2.28	2.28	2.80	2.28	2.83	2.28	16.72	24.32

[a]Space is unavoidably larger for the 0.76 mm size than is desirable (see text for explanation).

[b]There are only insignificant differences in character size for all element shapes.

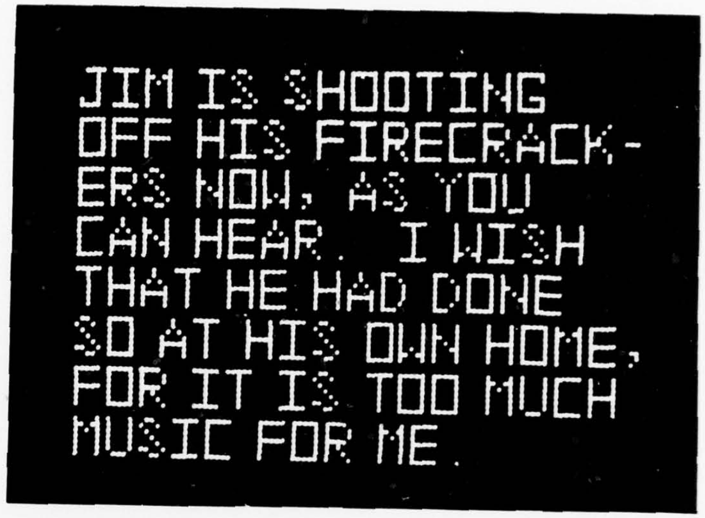

Figure 27. Smallest Spacing/Element Size Ratio Combination

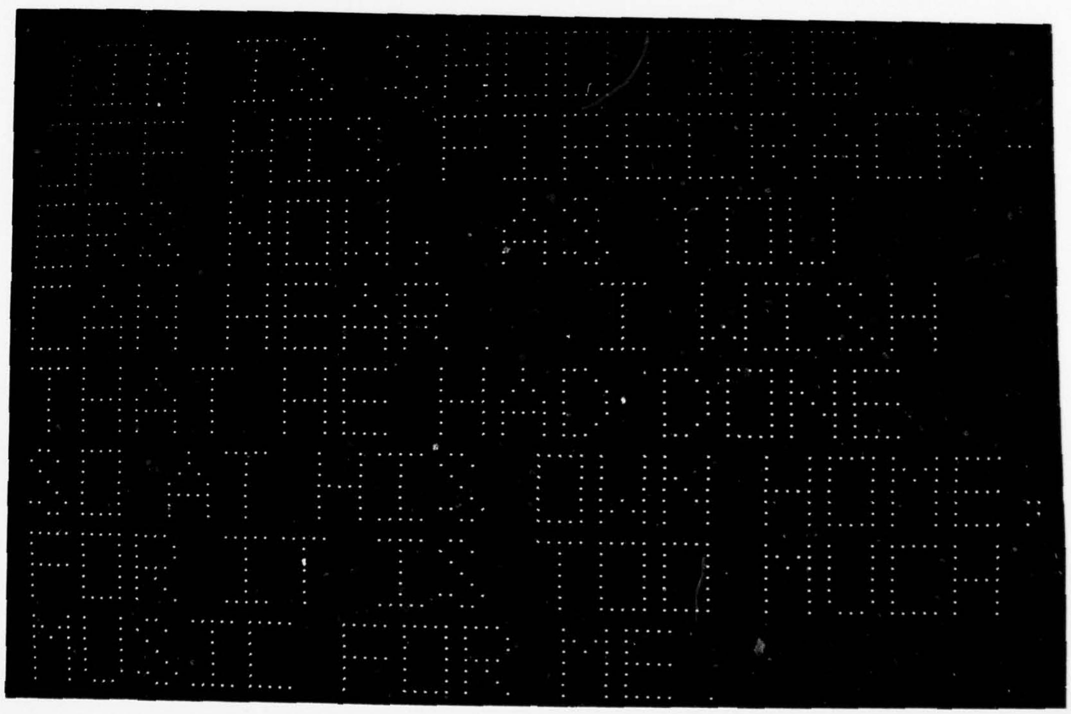

Figure 28. Largest Spacing/Element Size Ratio Combination

variables. These measures were a reading rate score and two search task scores, one random in two-dimensional location of the characters and one structured somewhat like a menu. The reading task was used because it is similar to the task a person faces when participating in a training course using computer-generated training passages and instructions. Also, an effort is being made to have computer programming languages written in dialog form and, therefore, be more widely usable. The random search task is similar to the situation on a Combat Information Center tactical display in which the user must search the display, usually in a random manner, to find the symbols or characters of interest. The other (menu) search was thought to represent a more structured task, such as a parts number search in a catalog. All three tasks, in other words, represent real-life situations.

The *Basic Reading Rate Scale* (Tinker, 1947) is a reading rate test taking five minutes (as revised by Carver, 1970). The test has been developed as an experimental tool for analyzing legibility variables (Buros, 1959). It has been shown to have high (r = 0.96) parallel forms reliability and has a high (r = 0.75) correlation with the *Davis Reading Test's Speed of Comprehension* variable. The content validity of the test would seem to be high due to the construction of the test, but an apparent weakness is the relatively small number of validation attempts. Specifically, only a few correlational studies have been performed, all by the author of the test.

The test consists of two parallel forms, A and B, with 98 and 97 passages, respectively. Each passage is made up of one or two sentences with a total of 30 words per passage. The subject is instructed to read as fast as possible and, as a comprehension check, to cross out one word in each passage that does not fit the meaning of the rest of the passage. The actual measure taken is the total number of passages completed at the end of five minutes. It is nearly impossible to finish all the passages within five minutes, and the material is simple enough so that few, if any, mistakes are made in crossing out the incongruous word.

As implemented in this research, the passages were taken from the Tinker *Speed of Reading Test*. Fifty passages from each form were given to each subject, one passage on the display at a time in the appropriate experimental variable combination (e.g., Figures 27 and 28). When the inappropriate word was found, the subject depressed the "Stop Clock" key and then spoke the incongruous word into a recorder. Responses were checked to verify that an unusual (> 4) number of errors was not made. Due to the time that it took the minicomputer to compile and print each passage, the entire test took about 25 minutes per form.

A search display consisting of three columns of eight "words" each was used for the menu search. Each word consisted of five randomly selected alphanumeric characters. One of the 24 words was the target. Once all of the words had been written on the display, an example of the target was written at the top center of the display, within a box. This signalled the start of the clock and told the subject which word to search for. The example remained on the screen throughout the trial to minimize memory requirements (Figure 29). All

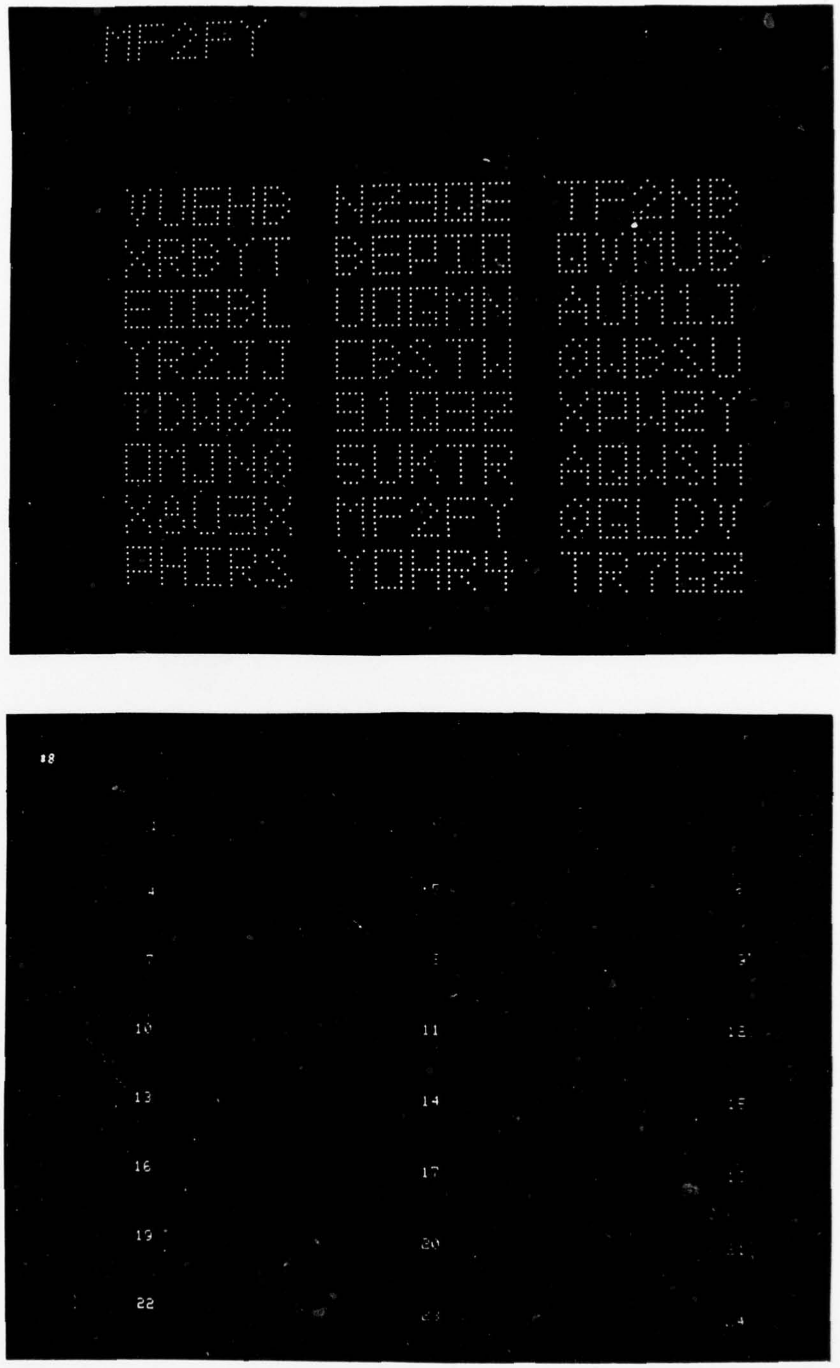

Figure 29. Menu Search Task: Search Display and Location Numbers

subjects received the same order of target locations for the 12 trials. This minimized between-subjects positional effects. To control positional effects further, the target was located once within each area of the display.

For the random search task, single nonoverlapping characters were positioned randomly on the display. All 36 alphanumeric characters were displayed constantly during a trial, with all but the target character displayed twice per trial. Therefore, there were 71 characters on the display at any one time. The display was divided into 12 equal areas and the target was located in each of the areas once for each subject. Again, as in the structured search, an example of the target was constantly displayed within a box, top center on the display, so that the subjects did not have to memorize the target but simply find it and give its location (Figure 30). All subjects received the same presentations of characters and all characters were oriented normally, that is, vertically.

For both search tasks, the performance measure was average search time per trial. This was computed by summing search times across all of the trials on which the subject found the target and entered the correct location. This sum was then divided by the total number of these correct trials per form for each subject.

The subjects' task was to locate the target and then press the "Stop Clock" key on the small keyboard directly in front of them. This response stopped the real-time clock in the computer. For the random search, pressing this key also caused a grid to appear on the display that divided the screen into 12 equal sections. Each section

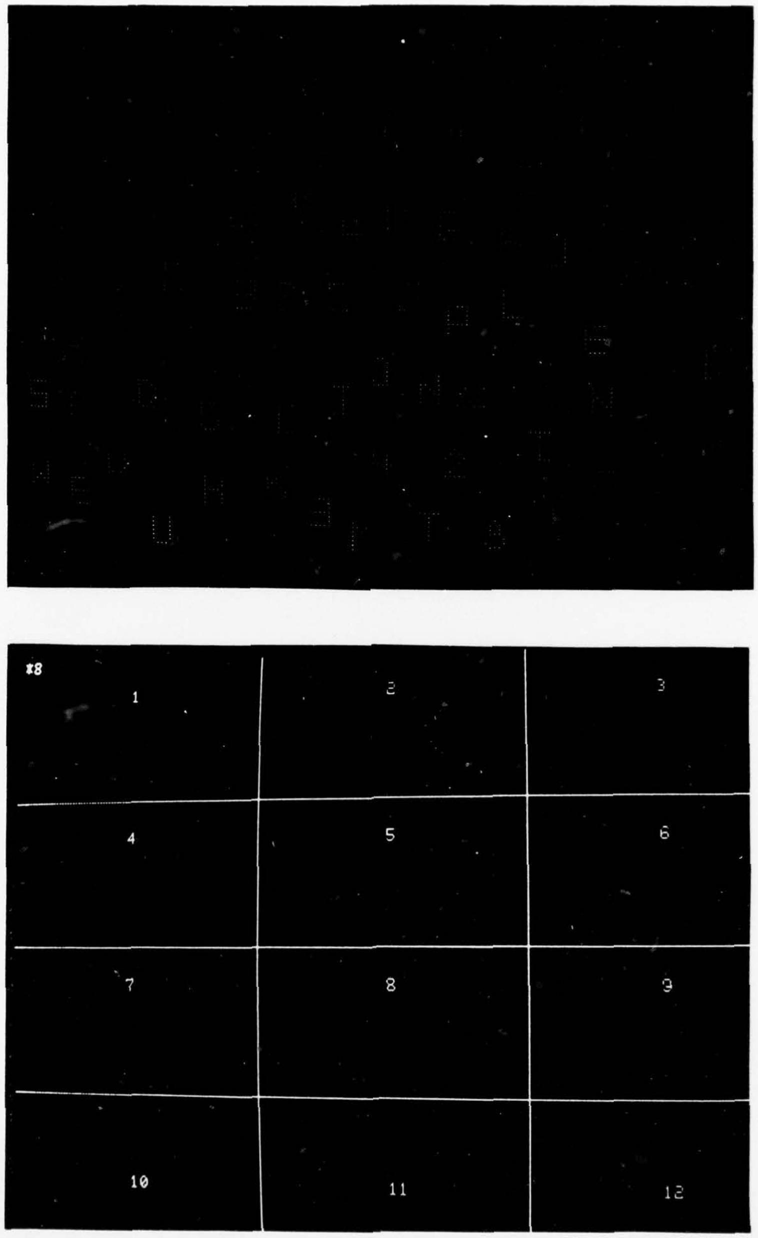

Figure 30. Random Search Task: Random Search Display
and Location Grid

was numbered and the subject entered the number corresponding to the target's location. It should be noted that the stimuli disappeared when the grid appeared (Figure 30). During the menu search, depressing the "Stop Clock" key caused a number between 1 and 24 to appear where each of the words was and the subject entered the target's location number on a small keyboard (Figure 29). For both search tasks, the subjects' responses were echoed on the display and, after correcting any typing errors, the subject initiated another trial by depressing the "Next" key on the small keyboard.

Laboratory equipment. The CRT display used for this research was the Tektronix 4014-1 direct view storage tube used in the previous experiment. The display had a green chrominance with a background luminance of about 2 cd/m^2, as measured in a darkened room. The points had a luminance near 17 cd/m^2, again measured in a room with low illumination.

The experiment was run and data were collected by the PDP 11/10 minicomputer with a 1.2 M word disc unit. A DEC Laboratory Peripherals System (LPS-11) was used for exact timing of operations. Data were output on a Centronix 306-C medium speed printer.

Experimental area. The display was located in an enclosed area 1.68 m by 2.13 m with a light-colored curtain on one side and light-colored walls on the other side and behind the display. Behind the subject was a dark-colored curtain to reduce extraneous reflections from the display's surface. If the subject wore light-colored clothing, a black drape was placed on the subject, again to reduce reflections.

Ambient lighting was provided by a fluorescent fixture with two 1.22 m tubes which diffused through an overhead screen at ceiling height for the higher lighting level. The lower ambient lighting level was provided by a small incandescent light diffusing through the same secreen. The higher level approximated typical office lighting and the lower level was near that of representative low lighting conditions.

Also in the experimental area were a subject's chair, a forehead restraint to position the subject's head at the desired viewing distance of 1.02 m, a tape recorder to record verbal responses, and a small keyboard mounted directly in front of the subject to be used to stop the timer and to record the target location in the search tasks.

Experimental procedure. The subjects were screened for acceptable vision before they reported for the single experimental session. Upon arriving for the session, each subject was seated in the experimental room where he/she read a set of instructions. During this time, his/her eyes were adapting (for 5-10 min) to the appropriate illuminance level.

Next, the subject was seated comfortably in the experimental cubicle and the head restraint was adjusted. Each subject received the reading test first under the appropriate conditions. Then the subject received the random and the menu search tasks, completing one type of search before starting the other. After both searches were finished, the ambient illuminance was changed and the same procedure of tasks was performed using the other forms of each task. The entire experimental session took approximately two hours per subject. At the end of each subject's session, a printout was obtained of the times per passage and per search for the subject as well as the incorrect responses that were made on the search trials. At the end of each subject's session, he/she received 10 additional passages at the high illuminance level written with characters generated internally by the Tektronix display. These were simulations of stroke-generated characters and were smaller than the experimental characters, so the subjects could read these passages faster than those in the rest of the experiment. These passages were used as baseline refinements to the reading time scores of each subject by subtracting the mean time of each subject's baseline passages from his/her experimental mean time per passage. This removed effects of individual reading speed.

Results

An analysis of variance was computed for each task using the *Statistical Analysis System*. Additionally, Newman-Keuls analyses of multiple comparisons were performed on any significant main effects and interactions to identify the significant differences. Appendix A lists the cell means associated with the 54 combinations of the experimental variables.

Tinker reading task. For each subject, the mean time per passage was computed. From this mean was subtracted the mean time per passage of the baseline reading task. The analysis of variance and Newman-Keuls computations were performed on these difference scores (Table 17).

The overall effect of element size was significant ($p < .05$), as shown by the analysis of variance. The 0.76 mm and the 1.14 mm elements produced approximately equal reading times, both of which were shorter (p < .05) than the time taken to read passages constructed of the 1.52 mm elements, as shown by Figure 31.

TABLE 17. Analysis of Variance Summary for Tinker Reading Test

Source of Variance	*df*	*MS*	*F*	*p*
Size (SI)	2	7.87	3.317	0.04
Shape (SH)	2	7.267	3.063	0.05
SI × SH	4	3.403	1.434	0.229
Space (SP)	2	30.733	12.954	0.0001
SI × SP	4	0.622	0.262	0.901
SH × SP	4	2.876	1.212	0.312
SI × SH × SP	8	0.916	0.386	0.925
Illuminance (I)	1	2.745	3.04	0.081
SI × I	2	1.917	2.123	0.124
SH × I	2	1.297	1.437	0.242
SI × SH × I	4	3.731	4.132	0.005
SP × I	2	1.34	1.484	0.231
SI × SP × I	4	1.871	2.072	0.091
SH × SP × I	4	1.318	1.459	0.221
SI × SH × SP × I	8	1.71	1.893	0.072
Total	53			

The effect of element shape was also statistically significant (p < .05). The square elements resulted in shorter times (Figure 32) than did the horizontally elongated rectangles (HER) (p < .05). The differences between the vertically elongated rectangles (VER) and the other shapes were not statistically significant (p > .05).

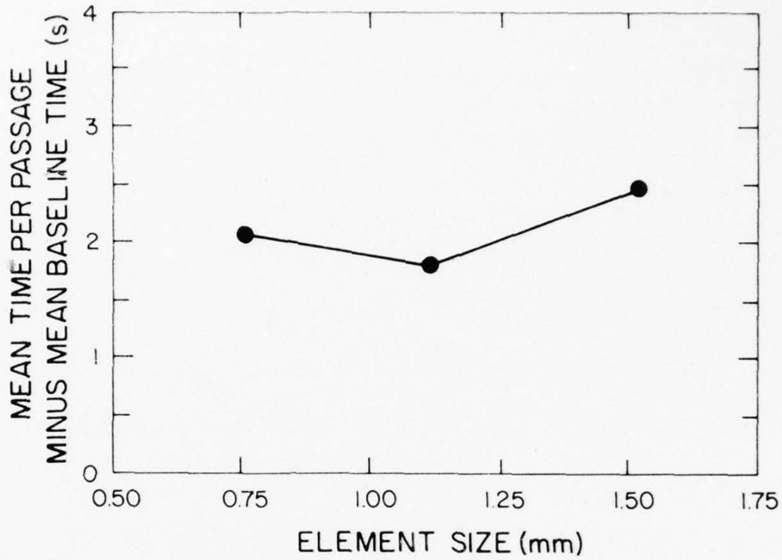

Figure 31. Effect of Element Size on Reading Time

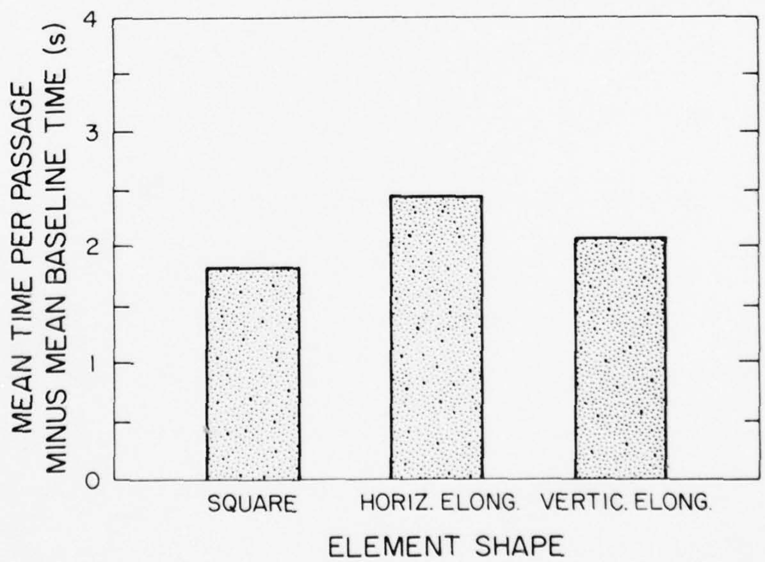

Figure 32. Effect of Element Shape on Reading Time

AD-A063 505 VIRGINIA POLYTECHNIC INST AND STATE UNIV BLACKSBURG --ETC F/G 5/8
INFORMATION TRANSFER FROM COMPUTER-GENERATED DOT-MATRIX DISPLAY--ETC(U)
OCT 78 H L SNYDER, M E MADDOX DAHC04-74-G-0200

UNCLASSIFIED HFL-78-3/ARO-78-1 ARO-12355.7-EL NL

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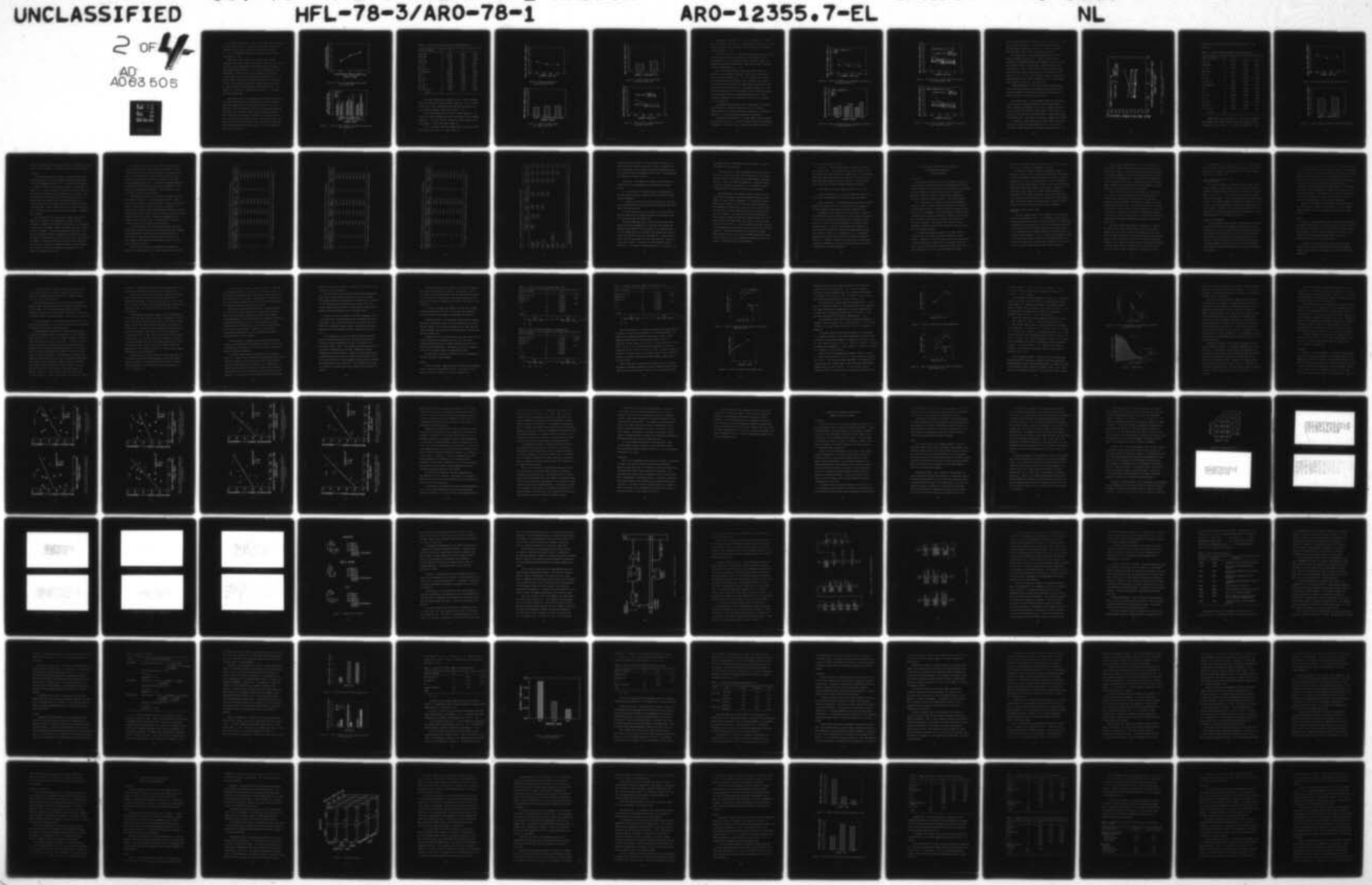



505

The highly significant ($p < .0001$), linear appearing space/element size ratio effect (Figure 33) indicates that the closer together the elements were, the quicker the subjects could read the passages ($p < .01$). All differences among the three means are statistically significant ($p < .01$).

Though the overall element size × element shape × ambient illuminance interaction is highly significant statistically ($p < .005$), there are only two combinations of the variables that are different enough from the other points ($p < .01$) to merit much attention. The largest HER (1.52 mm) at 700 lx is only different from the medium (1.14 mm) HER at 700 lx and the smallest (0.76 mm) HER at 5.4 lx. The greatest number of differences comes from the smallest (0.76 mm) VER at 700 lx, which produces significantly longer reading times than do all other combinations of the variables for the VER shape ($p < .01$) (Figure 34). There were no significant differences ($p > .05$) among the square element means.

Random search task. The average time per search for each subject was computed only from the trials during which the subject found the target and responded with the correct target location. Due to the closeness of some of the targets to the lines of the location grid and the potential for inadvertent errors in target location estimation, a correct location was considered to include any of the areas adjacent to, as well as, the actual target location. Of the 108 subjects, each having 24 trials (2160 trails total), there were only nine errors made and no single subject made more than one error. Table 18 summarizes the analysis of variance.

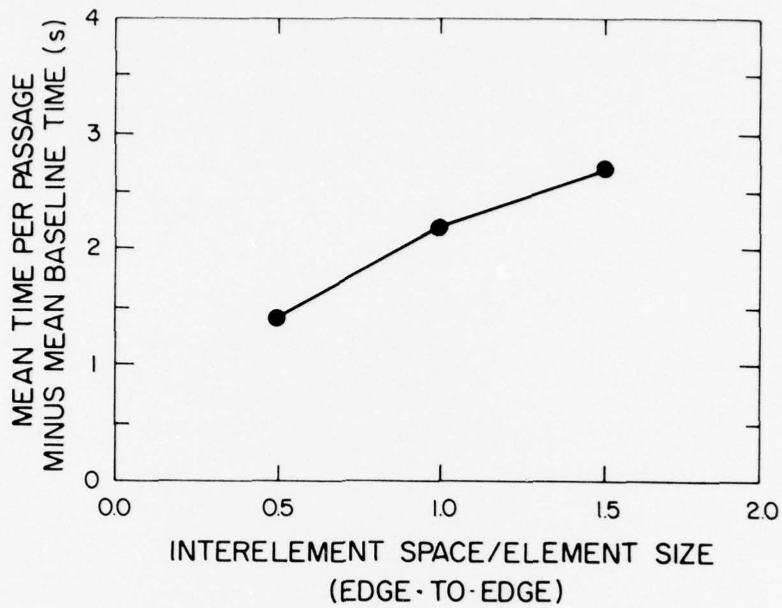


Figure 33. Effect of Interelement Spacing Ratio upon Reading Time

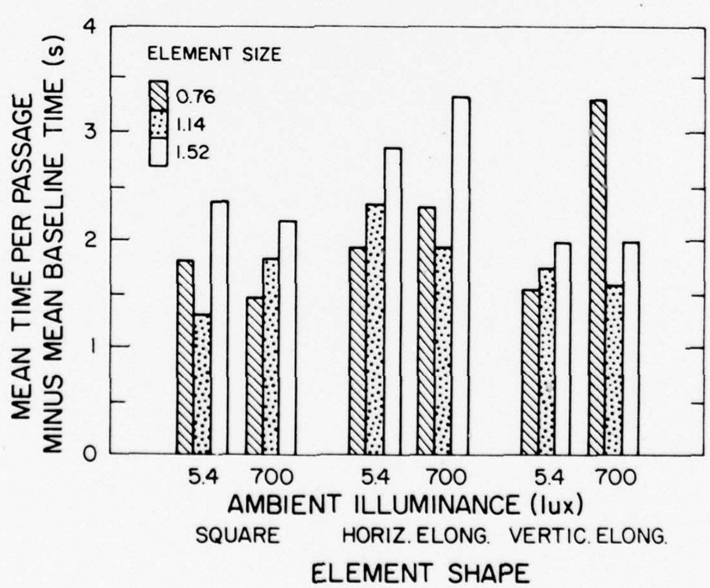


Figure 34. Effect of Size × Shape × Illuminance Interaction upon Reading Time

TABLE 18. Analysis of Variance Summary for Random Search Task

Source of Variance	*df*	*MS*	*F*	*p*
Size (SI)	2	116.451	13.843	0.0001
Shape (SH)	2	35.591	4.231	0.017
SI × SH	4	50.111	5.957	0.0005
Space (SP)	2	3.049	0.362	0.702
SI × SP	4	2.861	0.34	0.851
SH × SP	4	7.816	0.929	0.547
SI × SH × SP	8	23.23	2.761	0.01
Illuminance (I)	1	330.586	62.377	0.0001
SI × I	2	35.066	6.616	0.003
SH × I	2	19.969	3.768	0.026
SI × SH × I	4	14.88	2.808	0.03
SP × I	2	12.592	2.376	0.097
SI × SP × I	4	6.424	1.212	0.312
SH × SP × I	4	22.409	4.228	0.004
SI × SH × SP × I	8	23.515	4.437	0.0003
Total	53			

The overall significance of element size ($p < .0001$) was brought about by the effect of the small element (Figure 35). The 1.14 mm and 1.52 mm sizes are not significantly different from each other, while the 0.76 mm size produces longer search times ($p < .01$).

As with the reading task, the effect of element shape ($p < .02$) is due to the square element being better than either of the rectangular elements ($p < .05$), while the two rectangular elements produced essentially equal ($p > .05$) search times (Figure 36).

The 5.4 lx ambient illuminance produced much shorter search times than did the 700 lx level ($p < .0001$) (Figure 37).

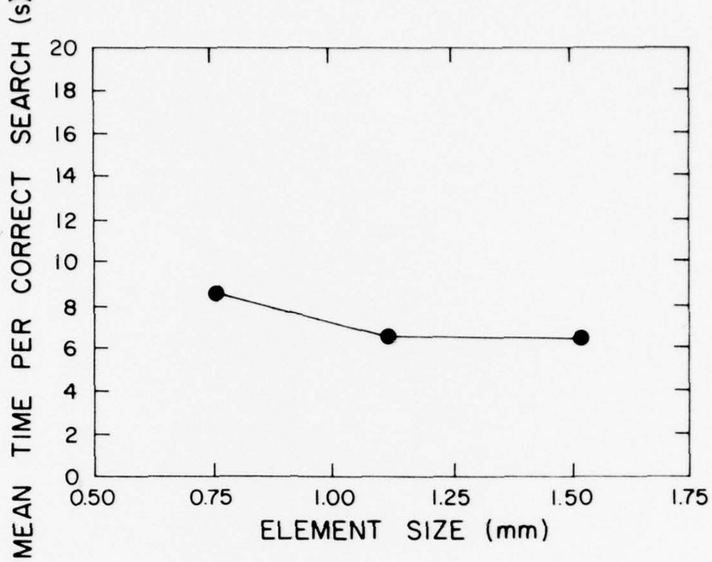


Figure 35. Effect of Element Size
upon Random Search Time

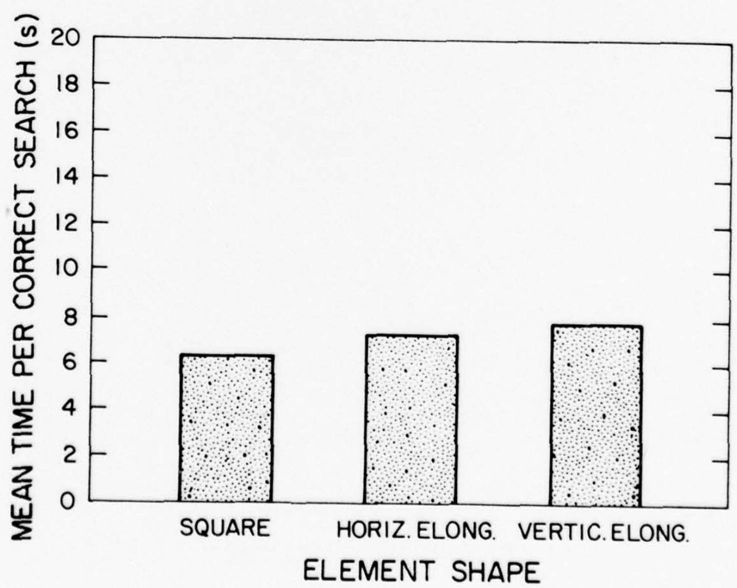


Figure 36. Effect of Element Shape
upon Random Search Time

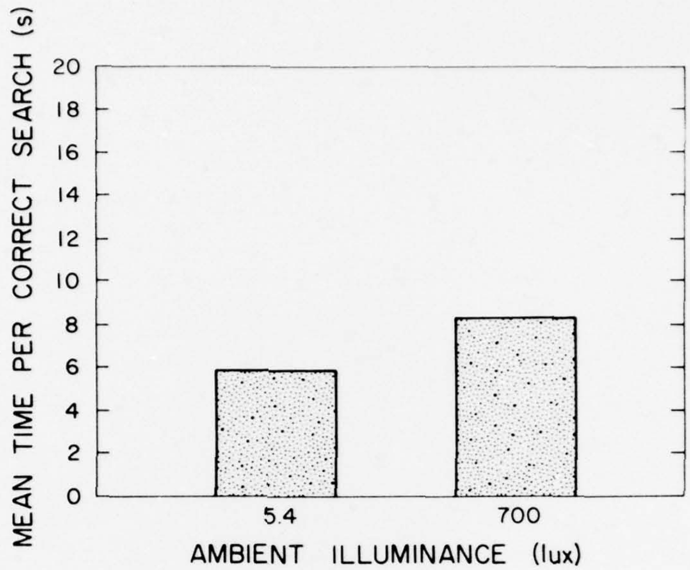


Figure 37. Effect of Ambient Illuminance upon Random Search Time

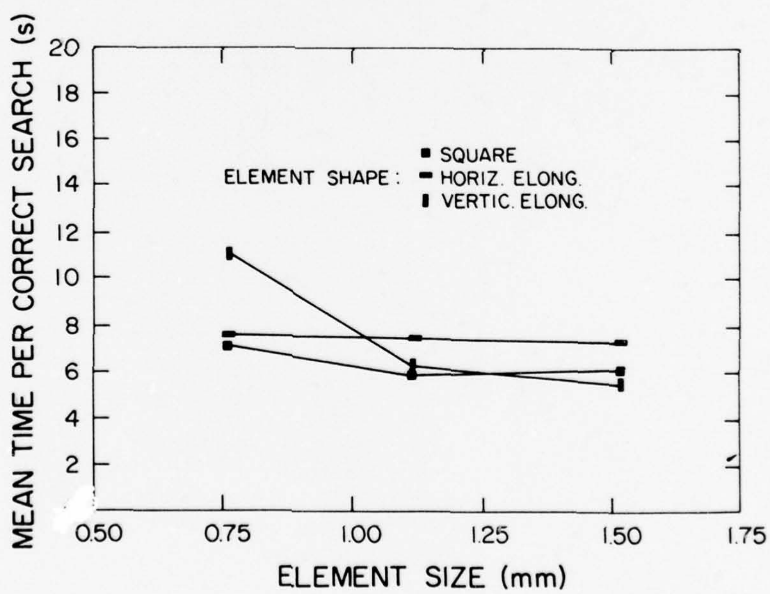


Figure 38. Effect of Size × Shape Interaction upon Random Search Time

Though highly significant ($p < .0005$), the element size × element shape interaction is caused by the small VER being so much worse ($p < .01$) than all the other means (Figure 38). None of the other means differed from one another ($p > .05$).

The entire element size × ambient illuminance interaction ($p < .003$) is caused by the mean search time for the 0.76 mm element at 700 lx being greater ($p < .01$) than the mean search time for all other size-illumination combinations (Figure 39). There were no other significant differences among the means ($p > .05$).

The square element produces shorter mean search times and is affected less by the higher illuminance level (700 lx) than either of the two rectangular elements ($p < .01$). This could be due to squares being more dense than are rectangles, but it should be noted that in this case the square actually has a slightly greater area than did the rectangles of the same element size. The overall interaction ($p < .03$) comes from the VER at 700 lx being different from all other combinations of element shape and ambient illumination except the HER at 700 lx; this latter combination is different from all three 5.4 lx conditions ($p <.01$) (Figure 40).

The seemingly complex element size × element shape × interelement space/element size interaction (Figure 41) ($p < .01$) is greatly simplified when it is realized that only the small VER is significantly different ($p < .01$) from the other experimental combinations.

The nature of the element size × element shape × ambient illuminance interaction ($p < .03$) is primarily related to only two experimental combinations. The VER at 700 lx is significantly different from all of

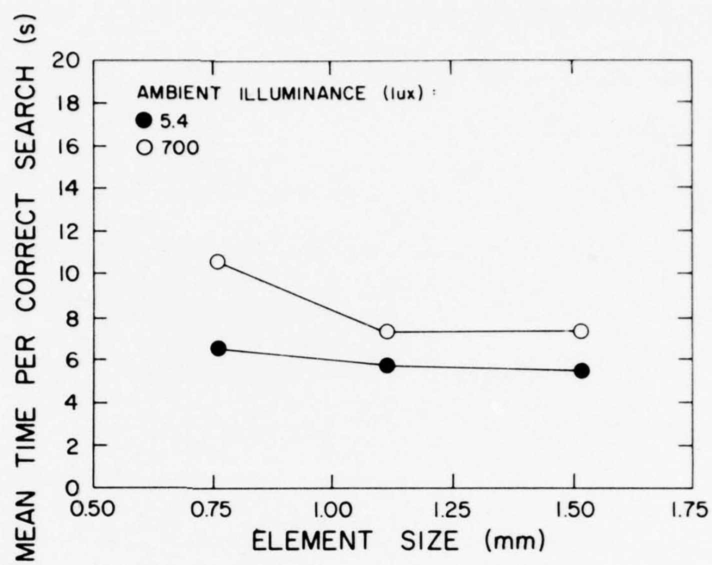


Figure 39. Effect of Element Size by Illuminance Interaction upon Random Search Time

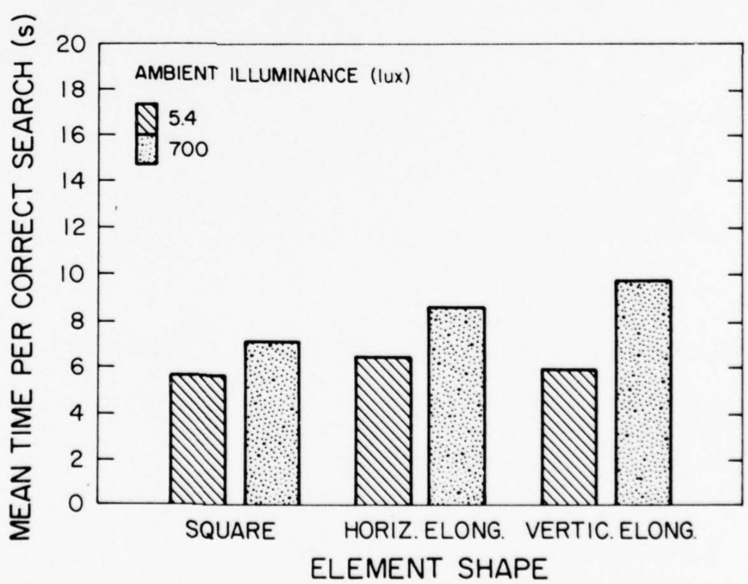


Figure 40. Effect of Element Shape by Illuminance Interaction upon Random Search Time

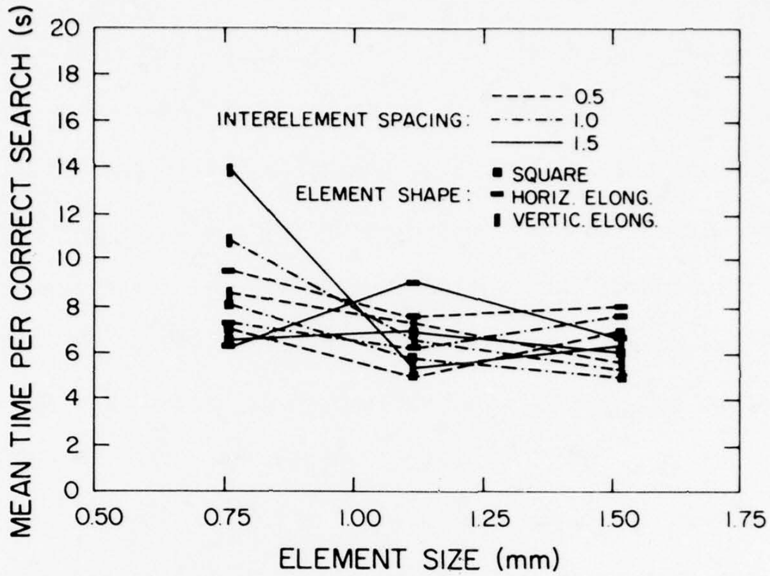


Figure 41. Effect of Size × Shape × Spacing Interaction upon Random Search Time

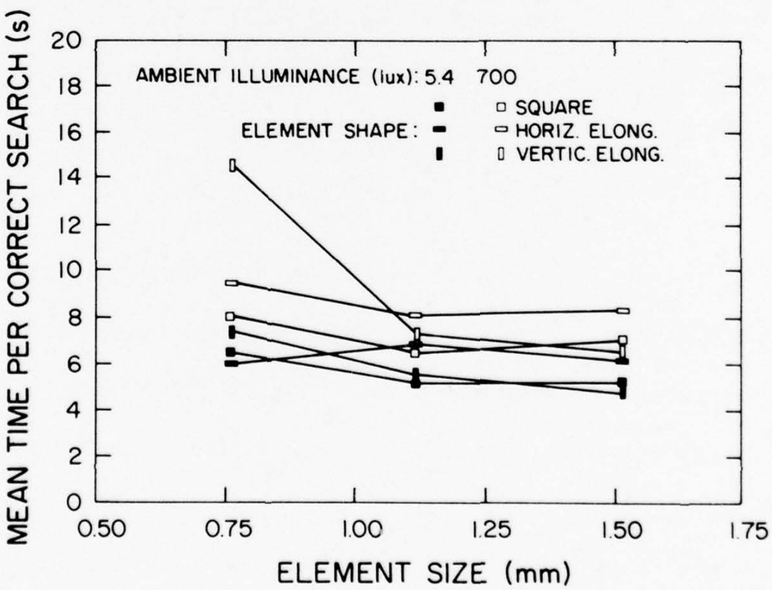


Figure 42. Effect of Size × Shape × Illuminance Interaction upon Random Search Time

the other shape-illuminance combinations at the 0.76 mm size ($p < .01$). The only other significant ($p < .01$) difference among all of the shape-illuminance combinations at any size is between the smallest HER at 700 and 5.4 lx for the 0.76 mm elements (Figure 42).

The element shape × interelement space/element size ratio × ambient illuminance interaction ($p < .0004$) was caused by four combinations of shape-spacing ratio and illuminance. At the 0.5 ratio, only the HER at 700 lx was significantly different from the other combinations ($p < .05$). At the 1.0 ratio, both the VER and the HER had significantly longer search times at 700 lx than did any of the shapes at 5.4 lx ($p < .05$). Only the VER at 700 lx was significantly different from all of the other combinations at the 1.5 interelement space/element size ratio ($p < .01$) (Figure 43).

Though significant ($p < .0003$), the four-way interaction has little practical value due to its complexity and because the entire interaction appears to be caused by the smallest VER coupled with some small effect of the HER, but only at 700 lx.

Menu search task. As with the random search, only the correct trials were used to compute each subject's mean time per search. A correct response was considered to be any of the numbers adjacent to, as well as, the actual target's location number. There were only 11 errors over the entire 2160 trials and, again, no single subject made more than one error. The analysis of variance is summarized in Table 19.

As with the random search task, the small element was the major cause of the element size experimental effect ($p < .01$), since it was slightly poorer than either of the larger element sizes ($p < .01$),

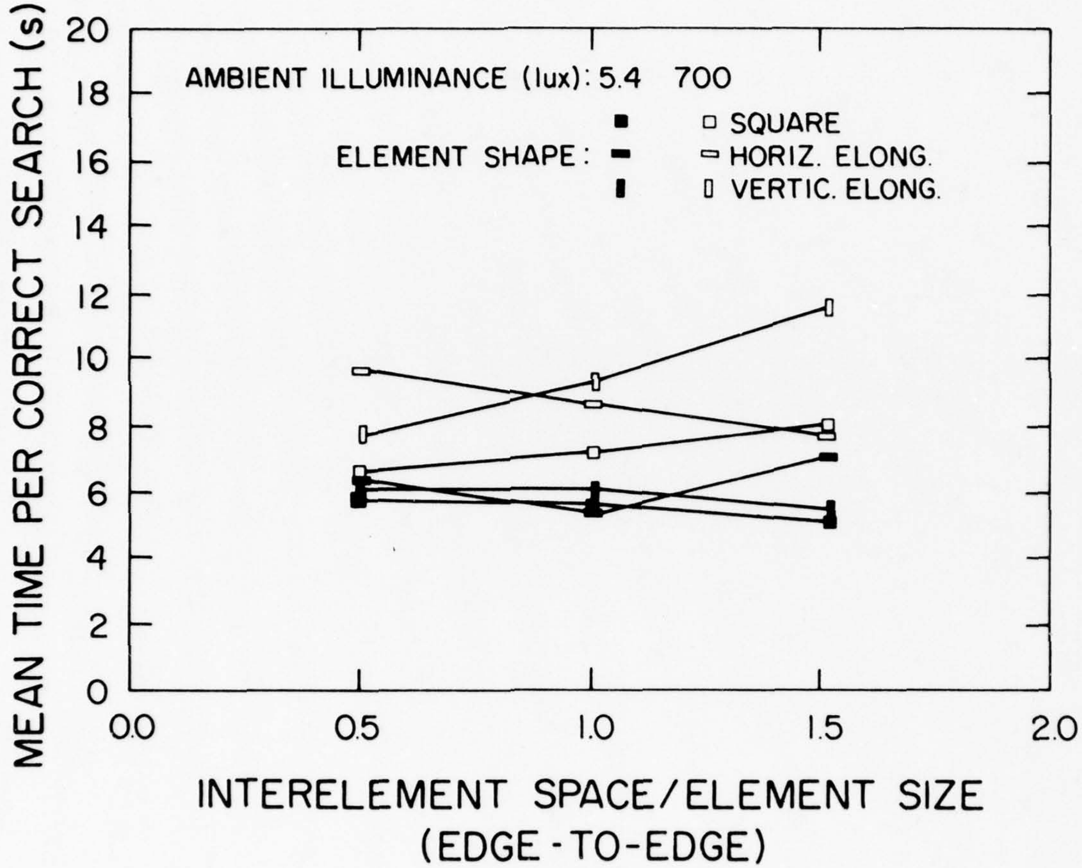


Figure 43. Effect of Shape × Spacing × Illuminance Interaction upon Random Search Time

which were not significantly different from each other ($p > .05$) (Figure 44).

TABLE 19. Analysis of Variance Summary for Menu Search Task

Source of Variance	*df*	*MS*	*F*	*p*
Size (SI)	2	16.681	4.795	0.01
Shape (SH)	2	8.643	2.484	0.088
SI × SH	4	2.041	0.587	0.676
Space (SP)	2	5.557	1.597	0.207
SI × SP	4	0.191	0.055	0.991
SH × SP	4	1.211	0.348	0.845
SI × SH × SP	8	2.259	0.649	0.735
Illuminance (I)	1	4.547	5.739	0.018
SI × I	2	0.898	1.133	0.327
SH × I	2	0.029	0.036	0.964
SI × SH × I	4	0.643	0.812	0.523
SP × I	2	0.119	0.15	0.862
SI × SP × I	4	1.057	1.334	0.263
SH × SP × I	4	0.551	0.696	0.6
SI × SH × SP × I	8	0.366	0.462	0.88
Total	53			

Though statistically significant ($p < .02$), the low illuminance level produced only slightly shorter search times than did the high illuminance level (5.78 and 6.07 s, respectively) (Figure 45). This

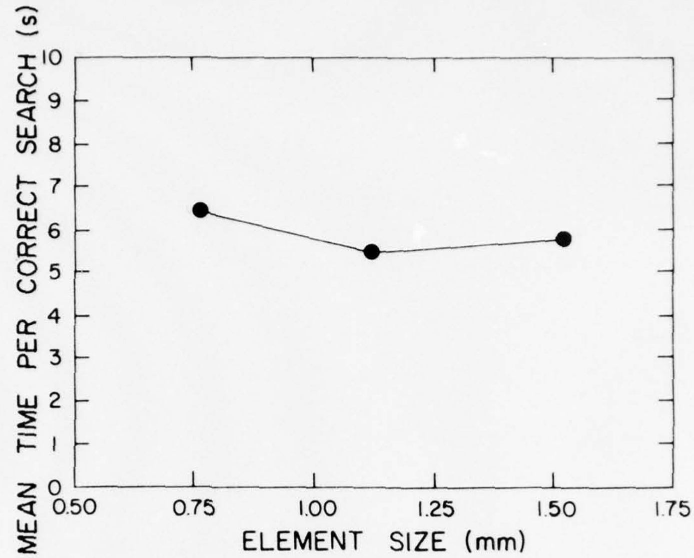


Figure 44. Effect of Element Size upon Menu Search Time

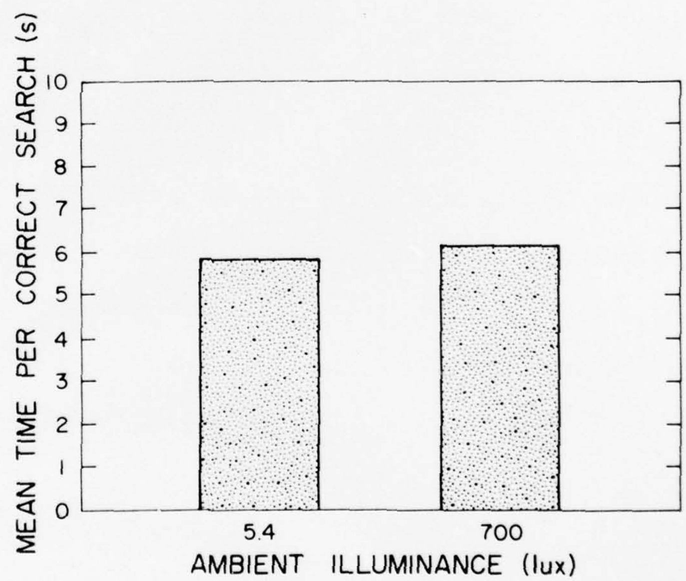


Figure 45. Effect of Ambient Illuminance upon Menu Search Time

difference, though statistically significant and in agreement with other results for this variable, is probably of little practical importance.

Discussion

One of the most consistent effects was that of the small VER. Because the smallest (0.76 mm) rectangular elements were made up of a vectored arrangement of points (i.e., 5×1 points for the HER and 1×2 points for the VER) and the points were less in width than in height (0.4×0.5 mm, respectively), the actual area of the small VER was much smaller than was that of the HER (0.24 *vs.* 0.39 mm^2). This smaller area was unfortunate, but unavoidable because the points on the display do not overlap enough to allow adding another row or column of these points to increase the area of the small VER to that of the small HER. Instead, adding such a row or column increases the area of the VER to an area greater than that of the HER. A compromise had to be made.

While the smaller VER's area perhaps created spurious interactions, it did point out the importance of element size upon performance. Related to the conclusion that element size is important is the fact that the largest element, the square, also led to the best subjects' performance. Left mostly unresolved by these data is the matter of the overall effect of element shape and whether the effects of shape result from differences in percent active area, total area of the element, or from some interaction involving the total character size, which is a necessarily confounded variable, as noted previously. Because of these intrinsic confoundings, some secondary *post hoc* analyses are appropriate and follow.

Values for character vertical subtense (Height), horizontal subtense (Width), height × width (Area), element width × element height/center-to-center interelement spacing^2 × 100 (Percent Active Area), and character height × width × percent active area (Area × Percent Active Area) were computed at each of the 27 size-shape-spacing combinations (Table 20). These derived independent predictor variables were then correlated with subjects' performances on all three tasks (reading and search tasks). Table 21 gives the r and associated p values for each correlation.

Performance on the Tinker test correlates reasonably well with both character height (r = .567) and character width (r = .563), as well as with the product of height and width (r = .560), simply because height is proportional to width for the various conditions. As character size increases, mean corrected passage reading time increases, probably because more visual fixations are required to cover the entire displayed area of the passage. It should be remembered that all characters were reasonably large (> 23 minutes of arc vertically), so that no acuity limits should have been involved.

Of interest, however, is the fact that the results from both search tasks correlate *negatively* with both height and width, although the correlations are significant only for the random search. As character size increases, search time decreases for these tasks. (This general result appeared in other studies as well, as will be noted in Sections IV and V.)

Better methods of predicting performance with individual characters on a display might use a Fourier analysis of the intensity

TABLE 20a. Character Subtense and Percent Active Area for the 0.76 mm Elements

Element Shape[a]	*Interelement Space/Size Ratio*	*Character Height(min)*	*Character Width(min)*	*Height × Width* (min^2)	*Percent Active Area*	*Height × Width × Percent Active Area*
S	0.5	25.62	17.93	459.37	44	20212.28
S	1.0	33.30	23.05	767.57	25	19189.25
S	1.5	40.99	28.16	1154.23	16	18468.48
H	0.5	23.93	17.93	429.06	29	12442.74
H	1.0	31.62	23.05	728.84	16	11661.44
H	1.5	39.30	28.16	1106.69	11	12173.59
V	0.5	24.54	15.50	380.37	18	6846.66
V	1.0	32.22	20.63	664.70	10	6647.00
V	1.5	39.91	25.75	1027.68	6	6166.08

[a]S = square; H = horizontally elongated rectangles; V = vertically elongated rectangles.

TABLE 20b. Character Subtense and Percent Active Area for the 1.14 mm Elements

Element Shape[a]	*Interelement Space/Size Ratio*	*Character Height(min)*	*Character Width(min)*	*Height × Width(min^2)*	*Percent Active Area*	*Height × Width × Percent Active Area*
S	0.5	38.42	26.90	1033.50	45	46507.50
S	1.0	49.95	34.58	1727.27	25	43181.75
S	1.5	61.48	42.27	2598.76	16	41580.16
H	0.5	36.00	26.90	968.40	30	29052.00
H	1.0	47.53	34.58	1643.59	17	27941.03
H	1.5	59.05	42.27	2496.04	11	27456.44
V	0.5	38.42	24.34	935.14	30	28054.20
V	1.0	49.95	32.02	1599.40	17	27189.80
V	1.5	61.48	39.71	2441.37	11	26855.07

[a] S = square; H = horizontally elongated rectangles; V = vertically elongated rectangles.

TABLE 20c. Character Subtense and Percent Active Area for the 1.52 mm Elements

Element Shape[a]	*Interelement Space/Size Ratio*	*Character Height(min)*	*Character Width(min)*	*Height × Width(min^2)*	*Percent Active Area*	*Height × Width × Percent Active Area*
S	0.5	51.23	35.86	1837.11	44	80832.84
S	1.0	66.60	46.11	3070.93	25	76773.25
S	1.5	81.97	56.36	4619.83	16	73917.28
H	0.5	47.53	35.86	1704.43	28	47724.04
H	1.0	62.90	46.11	2900.32	16	46405.12
H	1.5	78.27	56.36	4411.30	10	44113.00
V	0.5	51.23	32.36	1657.80	31	51391.80
V	1.0	66.60	42.60	2837.16	17	48231.72
V	1.5	81.97	52.85	4332.11	11	47653.21

[a]S = square; H = horizontally elongated rectanges; V = vertically elongated rectanges.

TABLE 21. Correlation of Secondary Variables with Dependent Variables

	Character Width	*Percent Active Area*	*Height × Width*	*Height × Width × Percent Active Area*	*Reading Test*	*Menu Search*	*Random Search*
Character Height	0.99[a] 0.0001	-0.36 0.0626	0.98 0.0001	0.70 0.0001	0.53 0.0048	-0.16 0.4298	-0.41 0.0315
Character Width		-0.34 0.0839	0.98 0.0001	0.71 0.0001	0.56 0.0023	-0.13 0.5204	-0.41 0.0328
Percent Active Area			-0.36 0.0644	0.33 0.0904	-0.77 0.0001	-0.53 0.0044	-0.30 0.1270
Height × Width				0.67 0.0001	0.56 0.0024	-0.09 0.6607	-0.38 0.0511
Height × Width × Percent Active Area					0.04 0.8455	-0.49 0.0096	-0.56 0.0024
Reading Test						0.53 0.0043	0.23 0.2524
Menu Search							0.70 0.0001

[a]The upper number of each cell is the correlation coefficient (r); the lower number is the p-value associated with that r.

distribution of the elements to derive the upper boundary of the modulation transfer function area (Snyder, 1973) or, perhaps a one- or two-dimensional Fourier analysis to determine unique power spectra most strongly related to performance (Pantle, 1974). These approaches are evaluated in Sections IV and V.

Tinker test. This reading test seems to be an accurate and sensitive metric for performance on visual displays for several reasons:

1. It is possible to refine the measure by subtracting the baseline time per passage to eliminate most of the inherent between-subjects differences;

2. Subjects are familiar with the reading-type test and there are no learning effects or other difficulties which might result from a more exotic measure; and

3. Such a reading task is very realistic in terms of future wide-scale applications of computer-generated visual displays, such as in training systems and computer I/O.

The main disadvantage seems to be that subjects became bored during the 25 min (approximately) of each form of the reading test. From the results gathered in this research, it was concluded that a 5-10 min reading test of 10-20 passages would probably have been just as valid and reliable as was this 50-passage test. Several subjects stated, after the experiment, that they could anticipate slightly the target word's location. Because of the small number of subjects reporting this, the probable random distribution of the subjects, and the apparent *post hoc* insignificance of such an effect, it was not considered in the data analysis.

Random search task. This task produced desirable results but was not as selective as was the Tinker reading task. Two or three subjects stated that they knew the target would appear in each area only once. Again, this random and apparently insignificant effect could only be ignored in data analyses. It is desirable, however, to debrief subjects to learn of such possible complications.

Menu search task. This measure was not as sensitive as the Tinker test or the random search task, probably because it was too simple. As several subjects commented, it was possible to observe and be able to recognize only the first two or three characters of each pseudoword to perform well on this task since it was not likely that more than one or two pseudowords in each trial began with the same first character. The range of the cell means reflected this effect because the menu search had a much smaller range (4.17-7.93 s) than did either the random search task (4.36-21.53 s) or the Tinker reading test (4.33-15.32 s). The task could have been more sensitive if more pseudowords were used and each word consisted of two or three characters. Another solution would be to constrain the random number generator in such a way that the random pseudowords were more similar; ideally, such target pseudowords would have only one or two characters different from the other pseudowords.

Design Recommendations and Conclusions

Element size. There was some difference between the reading and the search tasks. The smaller dots (and smaller characters) were more favorable to quick scanning with redundant cues, as in the reading task, while simple detectability was enhanced in the search tasks by using the larger elements (and larger characters). This difference must be taken into consideration when designing such displays.

Element shape. The square shape was the best in all cases.

Interelement spacing ratio. Again, scanning rate seemed to be critical for the reading task so the smallest space was the best.

Ambient illuminance. The enhanced luminance modulation resulting from the low luminance level (5.4 lx) was consistently superior to the lower modulation obtained with the higher illuminance level.

Of probably the most importance from the designer's viewpoint is the finding that the best condition for all three tasks was the medium sized (1.14 mm), square element with the small interelement spacing ratio (0.5). That is, for best performance, dots should be square and approximately 1.14 mm wide; edge-to-edge spacing should be no greater than 0.57 mm; and the displayed element/background contrast ratio should be at least 8.5:1 (modulation $\geq$ 0.79). This minimum modulation value agrees precisely with the conclusion expressed in Section II. Increases in element size and decreases in interelement spacing, the combination of which yields greater percent active area, lead generally to improved performance.

IV. PREDICTION OF INTELLIGIBILITY OF CONTEXTUAL AND NONCONTEXTUAL CHARACTERS: INITIAL EXPERIMENT

Introduction

The experiment described in Section II evaluated a variety of response measures in conjunction with two independent matrix display variables (character size and luminance level) through the presentation of single alphanumeric characters, while Section III described additional research on recognition of both single alphanumeric characters, clusters of nonsense characters, and entire sentences.

It is appropriate to concentrate on the single alphanumeric legibility studies, for these studies have application to the many situations where material is presented in other than language context with its built-in redundancy. On the other hand, one should be able to degrade a display (usually resulting in a monetary saving) further when the purpose of the display is primarily the presentation of contextual information. Consequently, such studies of single alphanumeric legibility do not directly translate to design criteria for the contextual situation.

It is generally conceded (Cornsweet, 1970) that stimuli of different shapes will affect the contrast threshold of a human observer. Therefore, it would seem logical that while the previously described research has its application, the data may not directly apply to any of the other display element point shapes being used or under consideration. We need a common denominator for human sensitivity to the matrix display of individual points or dots which, *when combined*, constitute an alphanumeric character.

To undertake a study involving the independent variables in Sections II and III, as well as other point shapes and a valid measure of contextual information transferred under each situation, would be a monumental task. Even if it were possible, it would be unthinkable that an additional effort might be necessary every time a new displayed element point shape became commercially available. Therefore, it is the purpose of this research to attempt to determine whether or not perception of matrix display parameters, such as point shape, point size, luminance, and point spacing, can be predicted through available image quality model methods; and, concurrently, to find an unbiased measure of the value of context to those display parameters.

Modulation Transfer Function (MTF) of the Eye

Any lens, imaging system, or even a human eye can be described by what has been termed the MTF. If, for example, one plots cycles/degree (spatial frequency) on the abscissa and modulation out/modulation in (referring to that modulation, or contrast, leaving and entering the system of concern) on the ordinate, most lenses and imaging systems will be characterized by a monotonic function, the MTF, which falls off at higher spatial frequency. This is a heuristically acceptable result, as most of us know that a television set or photographic camera will not pass the smaller details (higher spatial frequencies) of a scene as well as it will pass larger details (lower spatial frequencies).

There are some assumptions (those of linear systems analysis; see Cornsweet, 1970, pp. 324-330) involved in order to be able to use the term MTF. However, in situations where the assumptions are known to be violated somewhat, the same function described above as an MTF is called a "describing function." By using the latter terminology, we are only admitting that there is some error in the linear systems model. Whether we use the term MTF or describing function, a transfer function for the human visual system can be useful.

Such a transfer function can be plotted for the visual system if we present a sine-wave spatial pattern of 100% modulation at various spatial frequencies, and somehow obtain the subjective impression of that modulation. This method is analogous to that for determining the MTF of a lens or television system, but it is fraught with problems by virtue of the fact that "modulation out" in this case is subjective. Therefore, a more popular and appropriate procedure for determining spatial frequency sensitivity has been that of threshold measurement using standard psychophysical procedures (see Kling and Riggs, 1972).

When such threshold experiments are performed (e.g., Campbell and Robson, 1968; Patel, 1966), the human visual system exhibits a maximum sensitivity between 3 and 10 cycles/degree of visual angle. There are other factors that will cause this threshold curve to change shape, or shift sensitivity, but they are not of prime concern here. Therefore, if we compare the power specturm of the displayed information with human spatial frequency sensitivity data, we should be able to obtain an idea of the true distribution of frequencies and their associated amplitudes *as the human perceives them.* This combinatorial process is merely a method of attributing more weight to those spatial frequencies which appear within the more sensitive spatial frequency range of the eye (Snyder, 1973).

Display Parameters Critical to Power Spectrum Measurement

The critical parameters of any matrix display probably include display luminance, luminance contrast, dot size, spacing between dots (probably confounded with character height), character font, character matrix size (5×7, 7×9, etc.), refresh rate, display persistence, and display chrominance. All of these might affect the displayed power spectrum. Due to present hardware and practical constraints, it is not feasible to evaluate experimentally all factorial combinations of the above variables. Therefore, some selections were made for this first experiment on deriving a predictive measure of image quality. A more thorough approach will be presented in Section V.

Purpose of this Research

The first purpose of this research is to generate Fourier power spectrum data for some of the alphanumeric classes used in matrix displays, and to see if the resulting spatial frequency data hold any significance for human perceptual sensitivity (sensitivity data for these characters to come from the non-contextual portion of this research). Should the Fourier power spectrum data prove predictive of human performance, a possible means would exist of approaching matrix display assessment without unnecessarily extensive behavioral experimentation.

The second purpose of this research is to find an unbiased measure of the value of context to the matrix display parameters. Indisputably, there is a benefit to letters being arranged into word form, but further advantage or disadvantage may be realized when phrase or sentence meaning interacts with the human observer's background or expectations in any given situation. These interactions make the accurate assessment of context advantage nearly impossible, but it is desirable to try to make such a measurement in light of the fact that it is an obvious design concern. The importance of this aspect of the research is to determine whether and to what extent design criteria can be relaxed for the presentation of all contextual information.

Admittedly, the above two areas of matrix display research are not closely related. However, the intention here is to be somewhat broad in approach in order to contribute to the direction of future research.

Method

Subjects. Six paid subjects (3 male, 3 female) from the University and community population were screened for normal color vision and near and far acuity (corrected to 20/20 or better) by using a Bausch and Lomb Orthorater. Subjects ranged in age from 20 to 28 years. Each subject received 24 presentations under each of the 12 sets of experimental conditions, to be described below.

Apparatus. The principal apparatus consisted of the same Tektronix 4014-1 display terminal driven by the Digital Equipment Corporation (DEC) PDP 11/10 minicomputer, as well as the Model 2400 photometer.

In this experiment, the hardware-generated characters inherent in the terminal were used as opposed to characters which could be created in the manner described in Section III. Character heights were 2.64, 3.05, 4.79, and 5.44 mm.

These hardware characters (see Section II) are created from a Read Only Memory (ROM) device which uses a constant and smaller amount of the transfer rate. Refresh was accomplished by writing the characters repeatedly in the same location. Luminance was controlled by software control of the beam intensity at levels of 8, 24, and 66 cd/m^2.

Contextual advantage. To evaluate the contextual effect on the matrix display parameters, the data collection portion of the experiment was divided into two phases, anagrams and words.

The anagram phase consisted of the tachistoscopic presentation of four-letter anagrams under all 12 combinations of three luminances and four character sizes. Each of six subjects underwent 24 presentations under each of the 12 sets of conditions. The subjects were told that in a particular trial they would view four tachistoscopically presented letters which have been generated randomly. The score for a trial was accuracy, determined by the number of correctly recalled letters in the correct locations. The arrangement of letters in the anagrams was done carefully to avoid any vowel-consonant relationships that ordinarily appear in English. Mewhort (1969) has noted that pseudo-words are more perceptible than random letters. It was not expected that subjects would recognize the presented material as anagrams. However, by nature of the fact that the letters were "randomly generated," a single such occurrence should not have surprised the subject. Questioning subsequent to the experiment indicated that no subject was aware that the four letters were scrambled words.

During the word phase, the same subjects viewed the unscrambled words using the exact levels of the variables under which their anagrams were presented. The subjects were told that in a particular trial they would view four tachistoscopically-presented letters which constitute a word. The score for a trial was the same as in the previous phase.

The Thorndike and Lorge (1944) summary count of word frequency was used to compile the words for this phase. The material consisted of 144 four-letter words of high usage (greater than 100 per million words), and 144 four-letter words of lesser usage (less than 25 per million words). Each subject received random presentations from each of these two categories under each of the 12 sets of conditions, constrained such that 12 high- and 12 low-usage words occurred under each condition. The 288 words selected were viewed by all subjects, as words and anagrams; but, due to the random presentation, the order was different for all subjects. Half of the subjects viewed the anagrams first; half viewed the words first. Words and their anagram equivalents are given in Appendix B.

The score that was used to evaluate the context advantage was the mean word score minus the mean anagram score for each subject under each condition. This approach insured, as nearly as possible, that the difference in score between the words and anagrams was a result of context only.

Viewing conditions. Subjects viewed the display in a darkened room without the benefit of any filter over the display surface. The darkened room prevented glare and reflection which would otherwise be present when the filter is absent. Viewing distance was approximately 0.61 m, since most individuals find this to be the preferred distance for comfortable operation of this type of console.

Material was presented tachistoscopically. Exposure time was set at 16.7 ms by a pilot study prior to conducting the experiment. This time was the shortest obtainable given the present hardware system configuration. The brief presentation was used to hold constant the information entering the eye. It was not desirable to study mechanisms such as sub-vocalization or continued eye scanning which play roles in visual perception. Therefore, it was felt that tachistoscopic presentation was the most appropriate method for attaining the goals of this research.

Fourier analysis. The manner in which the spatial frequency spectra can be determined for an alphanumeric character is not at all straightforward. Therefore, this first look at spatial sensitivity should be considered elementary.

A circular scanning aperture (50 micron) and slit scanning device (25 × 2500 microns) were used in both the horizontal and vertical direction to measure a line of dots for each of the four character sizes at all three luminance levels (total = 48). Computerized Fourier analysis of these scans yielded a vertical and a horizontal power spectrum for each of the apertures at each character size and luminance. A 2.5X objective lens was used to make the display plane diameter for the circular aperture 20 microns. A 2.5X objective lens was used with the slit aperture.

The slit aperture scans were made by positioning the photometer eyepiece slit aperture parallel to the row of dots to be scanned. The luminance data from the photometer were recorded on an X,Y plotter as the scanning eyepiece was moved across the row of dots. The circular aperture scans were made in similar fashion, except that the aperture was moved through the center of sequential dots.

Procedure. Prior to beginning, each subject underwent a set of 12 training trials to acquaint him/her with the equipment and tasks to be performed. These trials allowed practice of responses until the subject felt comfortable enough to begin. The practice trials were offered prior to each additional session for those who felt a need for it.

At the beginning of a trial, the subject viewed the fixation box and instructions shown previously. By pressing the space bar, the subject caused a presentation to occur in the center of the fixation box (Ripley, 1975). The presentation followed the space bar activiation by approximately one second. Immediately following disappearance of the four letters, a number of random minipoints were activated within the area where the letters had been (Ripley, 1975). This action insured that residual phosphor discharge did not contribute any information after the presentation. This "stardusting" was done at just above the storage level of the CRT and was not noticed by any subjects.

After the presentation and "stardusting," instructions appeared for entering and verifying the response. By conducting a trial in this manner, the subject had control over the flash which was required to clear the screen. The flash was intense and irritating, but its effects were minimized by permitting the subject to look away or close his/her eyes.

As a subject responded, the complete trial data were recorded on hard copy generated by the TTY. At the same time, appropriate values were stored in the computer for subsequent data analysis.

Experimental design. The experimental design for both anagrams and words is factorial with all six subjects receiving every level of the four character sizes and three luminance levels. When analyzing context advantage, the data were the differences between the mean word and mean anagram scores.

Although there are two levels of point size, each with two levels of point spacings, this designation was not used. The nested relationship between these two variables makes the evaluation of an interaction term inappropriate. Therefore, four levels of character size (C) were initially used as the independent variable.

For data analysis purposes, characters size (C) and luminance (L) were both considered random variables.

Results

Context assessment. Separate analyses of variance were performed on word, anagram, and difference-score data. The results of those analyses are shown in Tables 22, 23, and 24, respectively.

TABLE 22. Analysis of Variance Summary for Word Scores

Source of Variance	*df*	*MS*	*F*
Character Size (*C*)	3	0.350405	1.37[a]
Luminance (*L*)	2	0.093774	1.50[b]
Subjects (*S*)	5	0.232272	
$C \times L$	6	0.042366	2.98[c]
$L \times S$	10	0.034399	
$C \times S$	15	0.056925	
$C \times L \times S$	30	0.014202	
Total	71		

[a] $F = \dfrac{MS_C}{MS_{CL} + MS_{CS} - MS_{CLS}}$, $df = 3,14$. [b] $F = \dfrac{MS_L}{MS_{CL} + MS_{LS} - MS_{CLS}}$, $df = 2,9$

[c] $p < .025$.

TABLE 23. Analysis of Variance Summary for Anagram Scores

Source of Variance	*df*	*MS*	*F*
Character Size (*C*)	3	0.761606	6.76[a,d]
Luminance (*L*)	2	0.475573	6.30[b,c]
Subjects (*S*)	5	0.831693	
$C \times L$	6	0.061061	3.19[c]
$L \times S$	10	0.033618	
$C \times S$	15	0.070673	
$C \times L \times S$	30	0.019144	
Total	71		

[a] $F = \dfrac{MS_C}{MS_{CL} + MS_{CS} - MS_{CLS}}$, $df = 3,13$. [b] $F = \dfrac{MS_L}{MS_{CL} + MS_{LS} - MS_{CLS}}$, $df = 2,8$.

[c] $p < .025$. [d] $p < .01$.

TABLE 24. Analysis of Variance Summary for Difference Scores

Source of Variance	*df*	*MS*	*F*
Character Size (*C*)	3	0.298611	2.28[a]
Luminance (*L*)	2	0.170428	1.69[b]
Subjects (*S*)	5	0.260879	
$C \times L$	6	0.070891	3.83[c]
$L \times S$	10	0.048582	
$C \times S$	15	0.078434	
$C \times L \times S$	30	0.018509	
Total	71		

[a] $F = \dfrac{MS_C}{MS_{CL} + MS_{CS} - MS_{CLS}}$, $df = 3,14$. [b] $F = \dfrac{MS_L}{MS_{CL} + MS_{LS} - MS_{CLS}}$, $df = 2,9$.

[c] $p < .01$.

Only the character size by luminance interaction was significant for the number of correct letters recognized in the word presentation. The significance was further evaluated by simple-effect *F*-tests. These comparisons showed that the variation among luminance levels is significant for the 3.05 mm size ($F = 6.66$, $p < .005$) and for the 2.64 mm size ($F = 5.79$, $p < .01$), and that variation among the size levels is significant only at 8 cd/m^2 ($F = 11.22$, $p < .001$). As shown in Figure 46, luminance is critical at only the two smaller character sizes; conversely, character size becomes significant only when luminance drops as low as the 8 cd/m^2 level.

Newman-Keuls multiple comparison tests (Myers, 1972) were employed throughout to determine significant differences among the means of those simple effects previously found significant. By this method, the mean

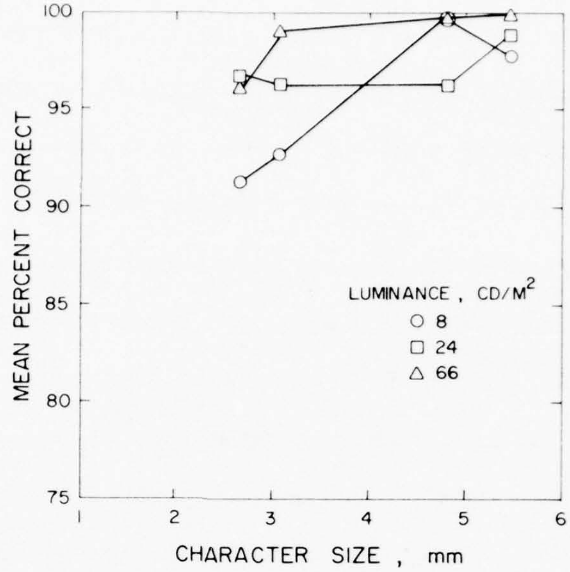


Figure 46. Effect of Character Size by Luminance Interaction upon Word Scores

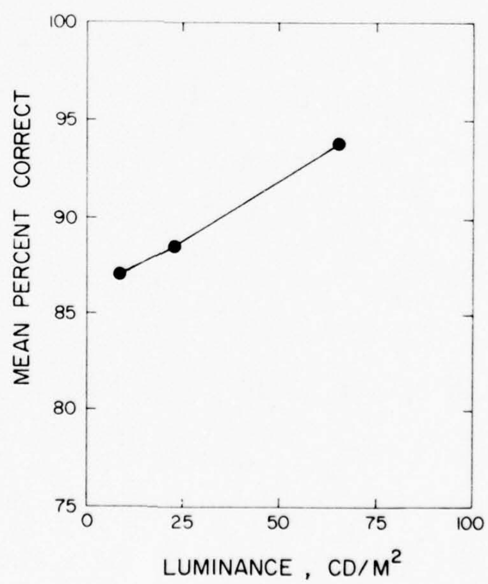


Figure 47. Effect of Luminance upon Anagram Scores

differences between 8 and 66 cd/m^2 and between 24 and 8 cd/m^2 were significant for 3.05 mm letters ($p < .01$). The only significant differences among the luminance means for 2.64 mm were those between 8 and either 24 or 66 cd/m^2 ($p < .05$). At 8 cd/m^2, 2.64 and 3.05 mm are significantly different from 4.79 and 5.44 mm ($p < .01$).

The anagram scores yielded significant differences for C, L, and the $C \times L$ interaction (Table 23). The luminance main effect (Figure 47) was further analyzed by the Newman-Keuls test, which showed that the 66 cd/m^2 mean is significantly greater than 24 or 8 cd/m^2 ($p < .05$), and that 24 and 8 cd/m^2 did not differ significantly ($p > .05$).

The significant C main effect is due to significant differences between 4.79 and 2.64 mm ($p < .01$), 5.44 and 2.64 mm ($p < .05$), 4.79 and 3.05 mm ($p < .05$), and 5.44 and 3.05 mm ($p < .05$), as illustrated in Figure 48.

In a manner similar to the word-score analysis, the significant $C \times L$ interaction (Figure 49) was further broken down into simple effect tests which indicated that luminance was important at 3.05 mm ($F = 4.92$, $p < .025$), and at 2.64 mm ($F = 24.32$, $p < .001$). At 3.05 mm, 66 - 8 cd/m^2 was found to be significant ($p < .05$), as were 66 - 8 cd/m^2 ($p < .01$) and 8 - 24 cd/m^2 ($p < .01$) at 2.64 mm.

While size at 8 cd/m^2 produced the largest F value ($F = 26.25$, $p < .001$), size at 24 cd/m^2 ($F = 12.71$, $p < .001$), and size at 66 cd/m^2 ($F = 7.20$, $p < .001$) were also highly significant. The evaluation of C at three levels of L revealed that 2.64 and 3.05 mm were significantly different from 4.79 and 5.44 mm ($p < .01$) at the lowest level of luminance, 8 cd/m^2; 2.64 and 3.05 mm were significantly different from

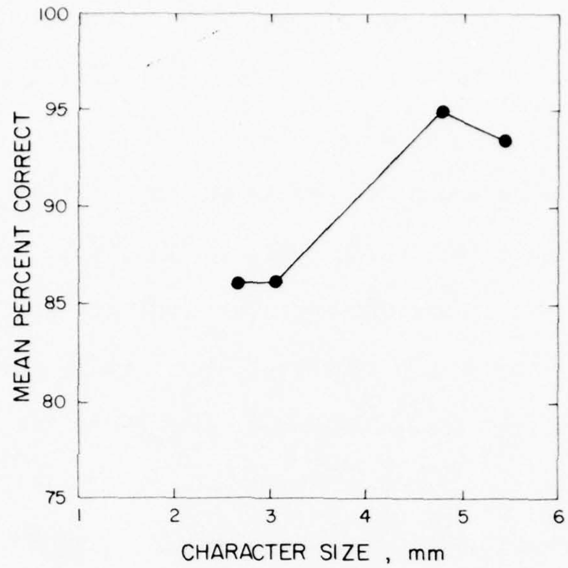


Figure 48. Effect of Character Size upon Anagram Scores

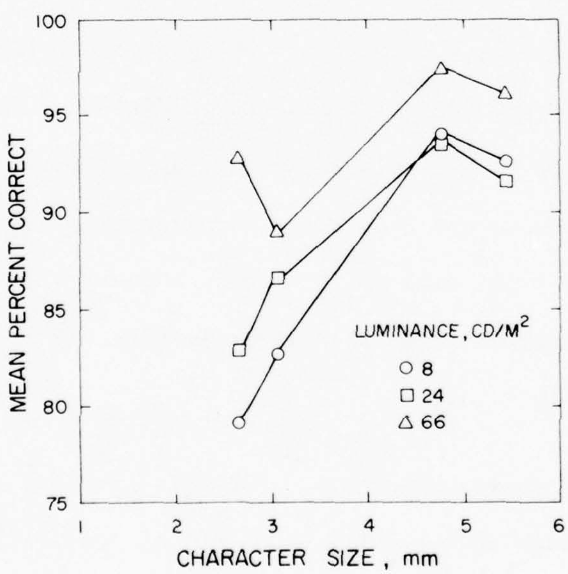


Figure 49. Effect of Character Size by Luminance Interaction upon Anagram Scores

4.79 and 5.44 mm ($p < .01$ for all but 5.44 - 3.05 mm, $p < .05$) at 24 cd/m^2; 5.44 and 4.79 mm were both significantly different from 3.05 mm ($p < .01$) at 66 cd/m^2.

The difference score data produced a significant $C \times L$ interaction (Table 24 and Figure 50), which leads to the simple-effect conclusion that luminance is an important contributor to the difference between words and letters only at a character size 2.64 mm ($F = 16.90$, $p < .001$). The Newman-Keuls test showed 24 and 8 cd/m^2 to be significantly different from 66 cd/m^2 ($p < .01$) for 2.64 mm letters.

Again, the effect of size was significant at 8 cd/m^2 ($F = 5.39$, $p < .005$), 24 cd/m^2 ($F = 12.02$, $p < .001$), and 66 cd/m^2 ($F = 6.38$, $p < .005$), but the nature of the size effect varied with the luminance level (Figure 50). At 8 cd/m^2, 2.64 - 5.44 mm ($p < .05$), 2.64 - 4.79 mm ($p < .01$), and 3.05 - 4.79 mm ($p < .05$) proved significant. At 24 cd/m^2, 2.64 and 3.05 mm are both significantly different from 4.79 mm ($p < .01$). 5.44 - 4.79 mm ($p < .05$) is also significant at 8 cd/m^2, but at a lesser level of confidence, and 2.64 mm is significantly different from both 5.44 mm ($p < .01$) and 3.05 mm ($p < .05$). However, at the highest luminance, 3.05 mm deviated significantly from all other levels of character size ($p < .01$).

Spatial frequency analysis. Probably the most investigated and validated approach to obtaining a perceptual sensitivity measurement based upon power spectrum and human threshold data is through the concept of the modulation transfer function area (MTFA) (Snyder, 1973). MTFA is simply the area between the modulation transfer function (MTF) or power

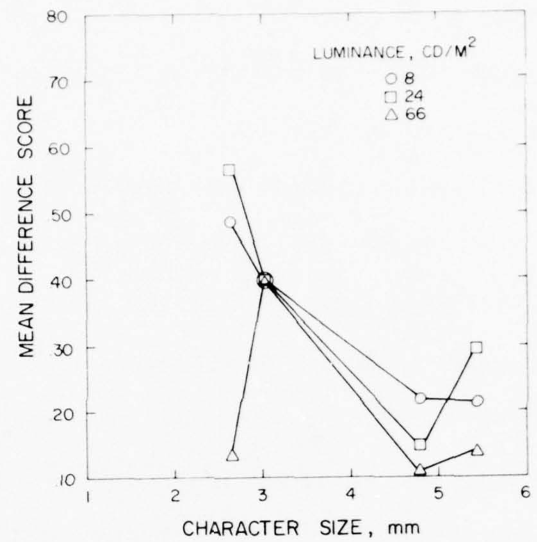


Figure 50. Effect of Character Size by Luminance Interaction upon Difference Scores

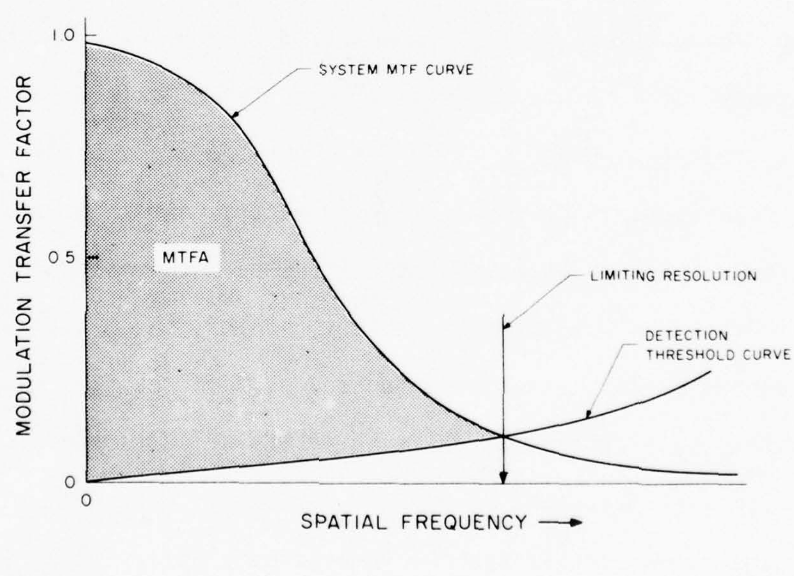


Figure 51. MTFA Concept

spectrum of an imaging system and the empirically determined threshold detectability curve of the human observer (Figure 51). In this type of analysis, perception or the quality of the image is correlated with the area between the two curves.

The scan data were converted for computerized Fourier analysis and subsequent area calculations, assuming a continuous function of the spatial frequency spectrum. A threshold detectability curve was approximated for application in these calculations from data of Campbell and Robson (1968). Area calculation was performed according to the common trapezoidal rule, and printed in the program output. Since the eye typically responds in proportion to the logarithm of energy impinging upon it (Graham, 1966), these data were calculated for both logarithmic and linear units. In the linear calculation, units of the abscissa were cycles/deg (of spatial frequency); units of the ordinate were percent (modulation). The logarithmic calculation was accomplished by transforming linear X and Y values to $\log_{10}$ prior to area calculations.

Regardless of whether or not such area calculations correlate with the perception of words, it was deemed inappropriate to use the word scores. As evidenced by earlier results, the presentation of four random letters resulted in poorer performance than that obtained when those same letters at the same levels of character size and luminance were presented as words. Obviously, the spatial frequency of an individual letter was the same in each case. Therefore, the correlations presented here are with mean anagram scores (to eliminate contextual effects) taken across all subjects (resulting in $4C \times 3L$ = 12 means).

Attempts to correlate the mean transfer function area, for a particular C - L combination, with the mean anagram score for that combination were relatively unsuccessful. Figures 52, 53, 54, and 55 show the plotted values and the linear regression best-fit line using the transfer function area as described above.

Careful reflection yields a possible reason for the absence of higher correlation. By scanning the letters in the manner described above, we have developed data for the individual point (or dot) contained in the 7 × 9 matrix, but not for the relative *amount* of that spatial frequency information contained in each letter. Therefore, to weight the spectral power for the amount of such power per character, the vertical angular subtenses of the four character sizes were multiplied by the area previously obtained. Revised plots based on this concept are shown in Figures 56, 57, 58, and 59, respectively.

As shown in these plots, the prediction of anagram letters is predicted well by both slit (r = 0.61) and circular aperture spectra (r = 0.72) on linear scales, and even better on log-log scales (r = 0.82 and 0.81, respectively).

Discussion

Evaluation of context advantage. The effects of luminance and character size are much as expected. In the anagram portion of the experiment, in which the letters are noncontextual and relate to such tasks as recognizing map coordinates or symbols, recognition of letters is affected strongly by luminance when the letters subtend 17 min or less (2.64 and 3.05 mm). At character sizes of 27 min and above (4.79 and 5.44 mm), luminance plays a less important role. Thus, an

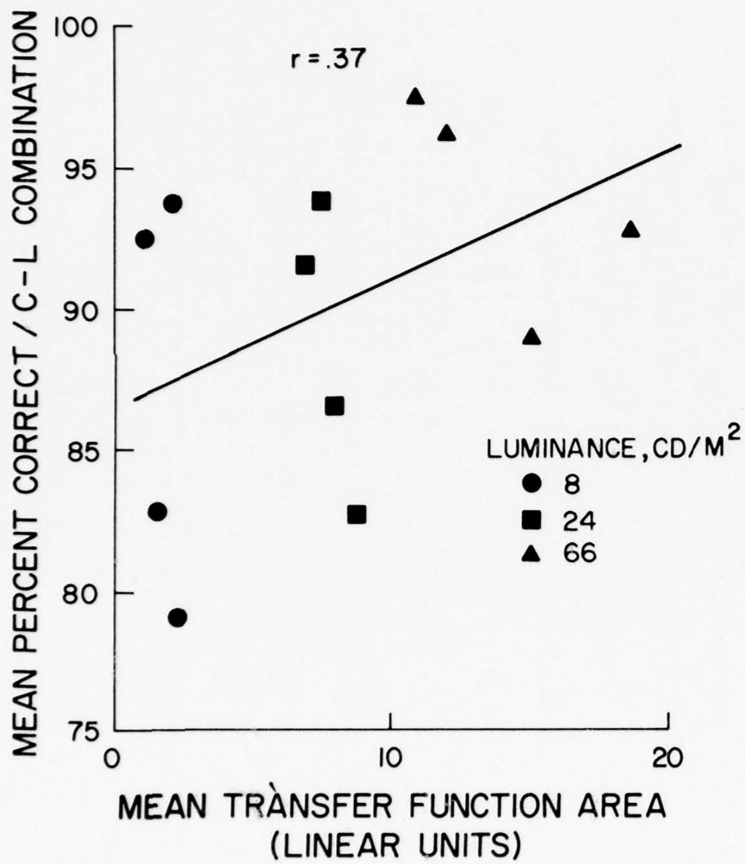


Figure 52. Correlation between Anagram Scores and Transfer Function Areas, Slit Aperture

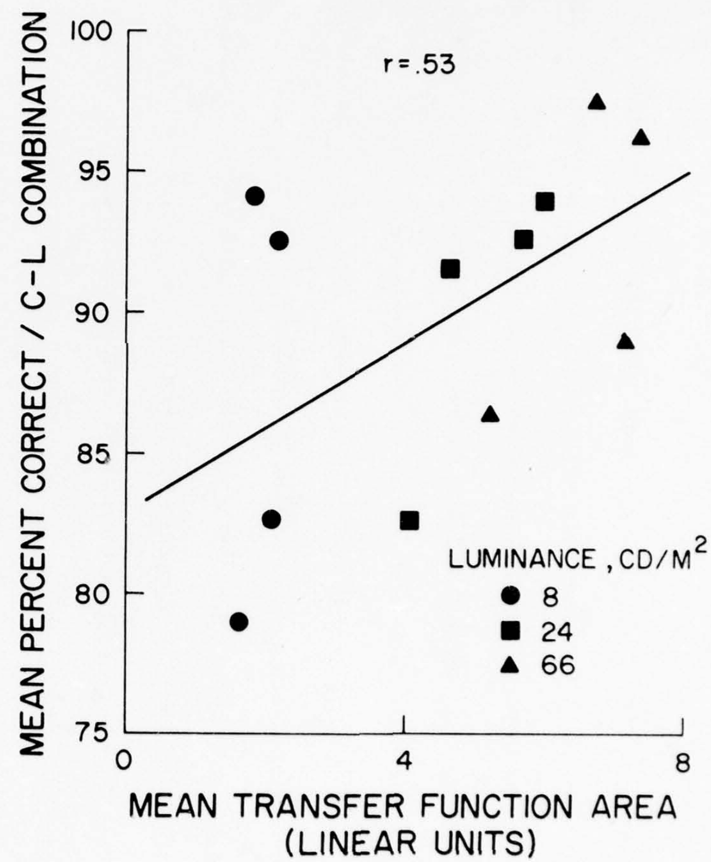


Figure 53. Correlation between Anagram Scores and Transfer Function Areas, Circular Aperture

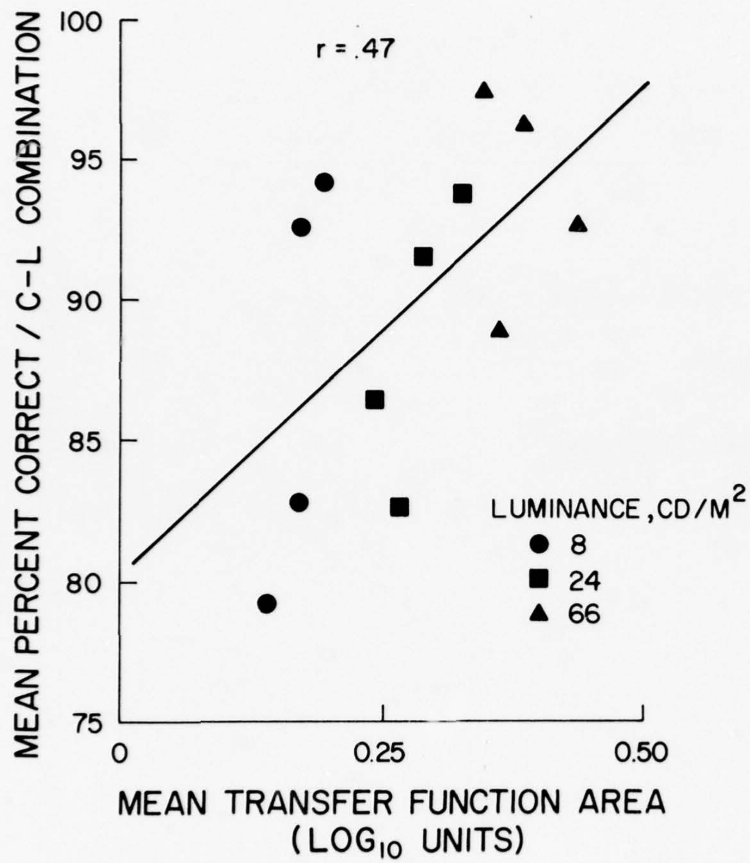


Figure 54. Correlation between Anagram Scores and Transfer Function Areas, Slit Aperture, Log_{10} Transformed

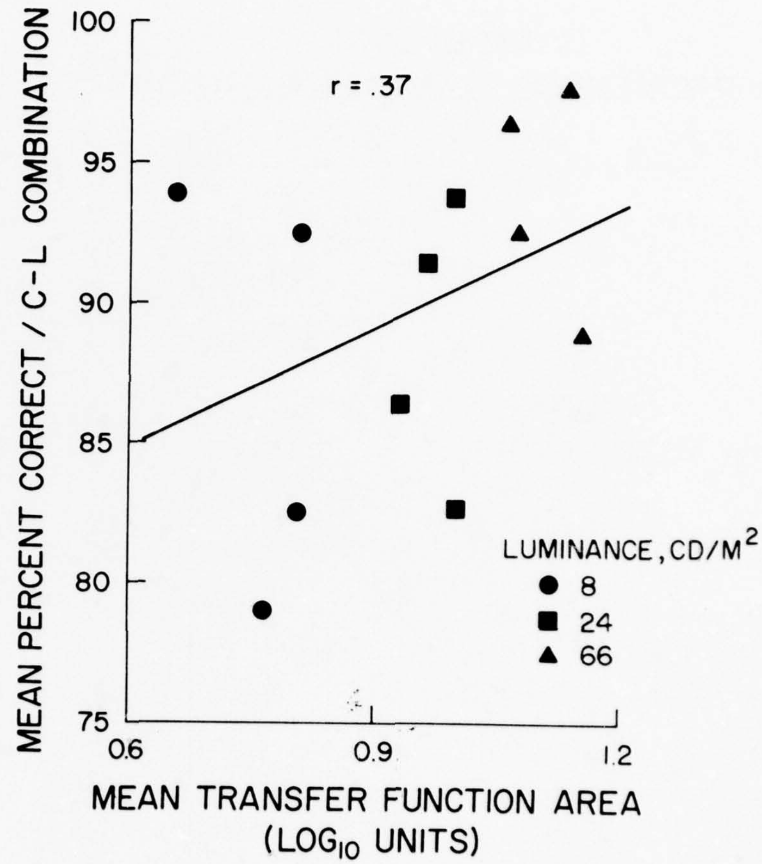


Figure 55. Correlation between Anagram Scores and Transfer Function Areas, Circular Aperture, Log_{10} Transformed

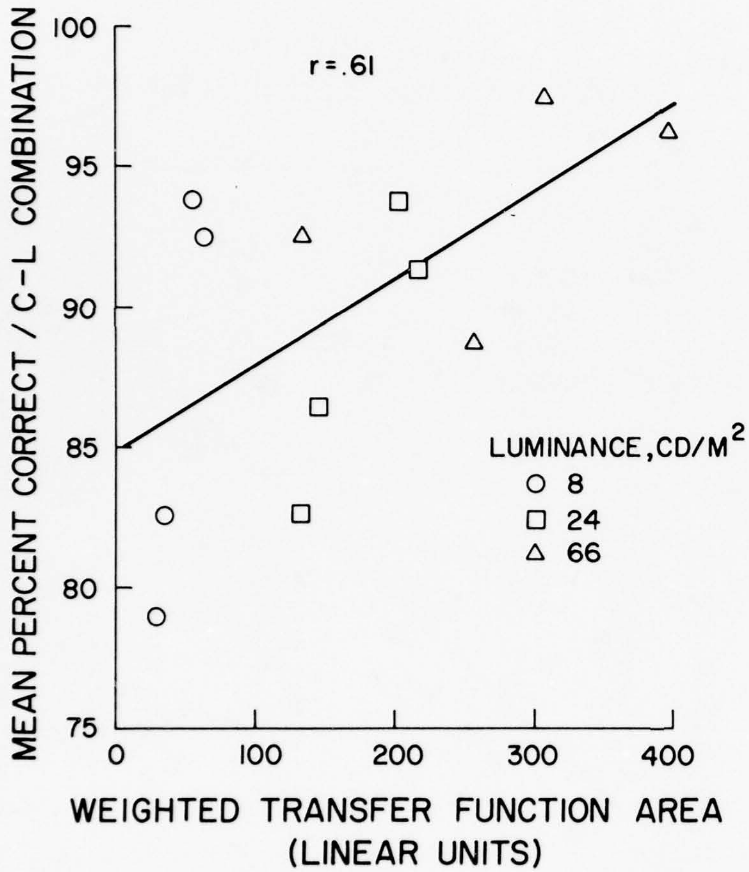


Figure 56. Correlation between Anagram Scores and Weighted Transfer Function Areas, Slit Aperture

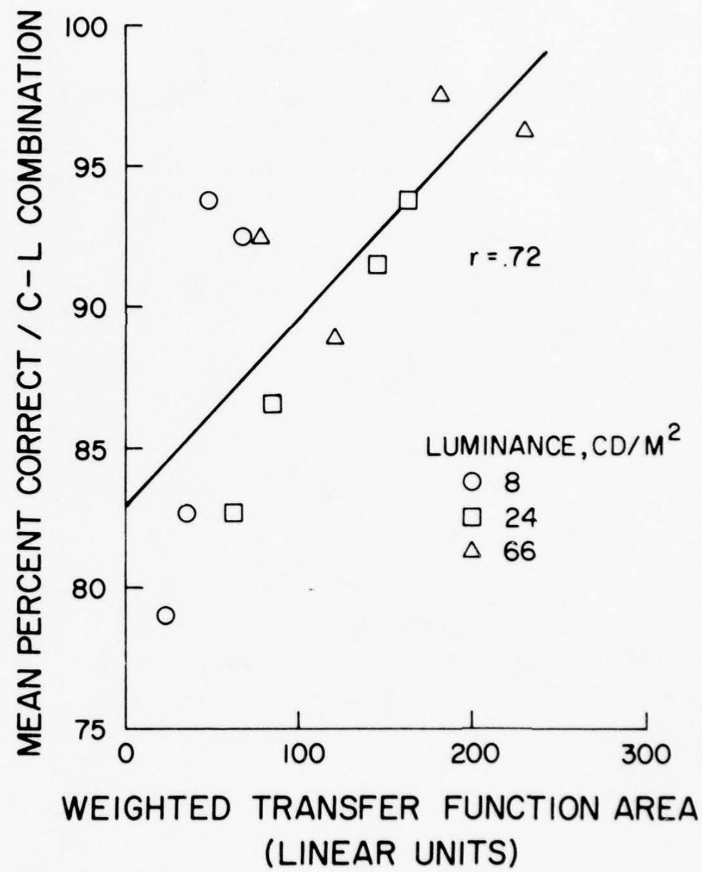


Figure 57. Correlation between Anagram Scores and Weighted Transfer Function Areas, Circular Aperture

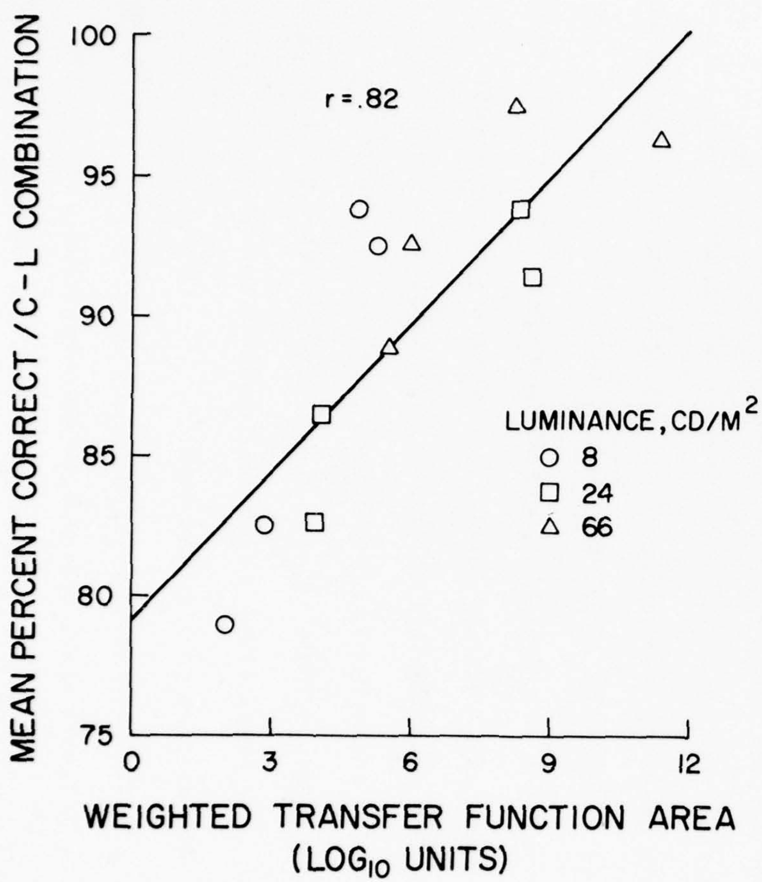


Figure 58. Correlation between Anagram Scores and Weighted Transfer Function Areas, Slit Aperture, Log_{10} Transformed

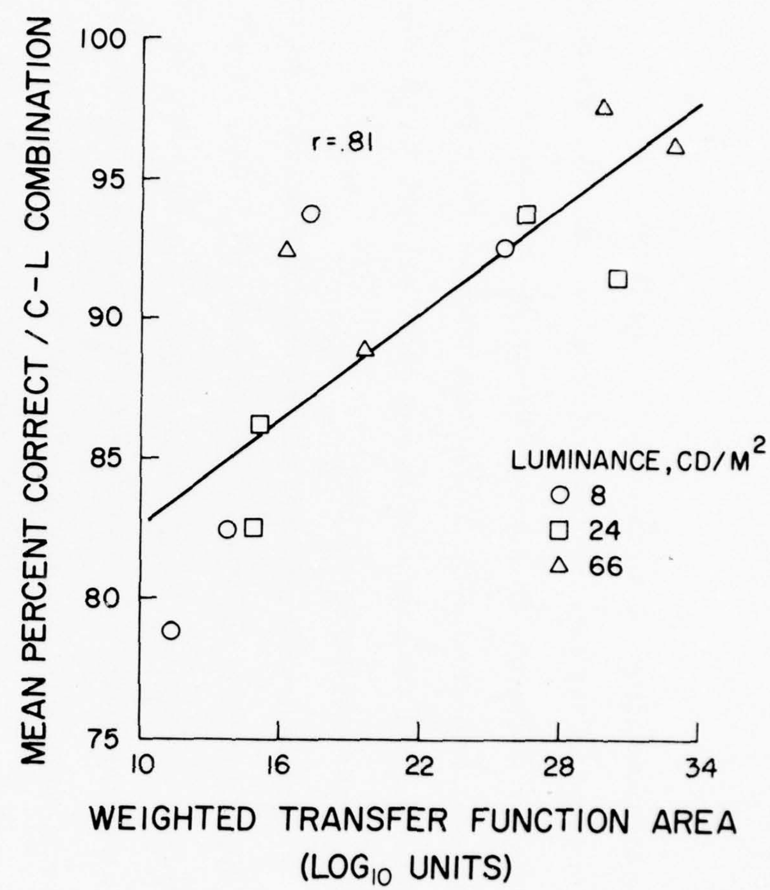


Figure 59. Correlation between Anagram Scores and Weighted Transfer Function Areas, Circular Aperture, Log_{10} Transformed

apparent trade-off between luminance and character size exists and is bracketed in the data. Extrapolation from these data should be possible to situations in which the displayed alphanumeric material is not of a contextual form, the accommodation of the viewer's eye is approximately the same as that used here, and symbol context is similar to the contrast used here.

Comparisons of significant main effects and interactions from the Section II data and those of the anagram data in this study are favorable. In Section II, it was shown that the character size by luminance interaction was significant, with the largest degradation in recognition of single alphanumeric characters coming at the small letter sizes (17 min) when modulation was less than 0.78. Data taken in the anagram portion of this study indicate that modulation values of 0.75 or less are adversely affected by character sizes subtending 17 min or less. In Section II, it was also reported that the same general difference in performance existed between characters subtending 17 min and those subtending 27 min. This result supports the hypothesis that the anagram letter arrangements essentially represent noncontextual material to the subjects.

The three levels of luminance resulted in modulations of approximately 0.38, 0.75, and 0.90. Consequently, the findings of Howell and Kraft (1959), discussed earlier, are also consistent with the results from the anagram task.

As anticipated, the presentation of words sustained performance over C,L levels where degradation had been noted with anagrams. Referring to Figure 50, it is clear that the (word-anagram) difference score was positive for all 12 C,L combinations, and significantly greater than zero ($t = 39$; $df = 11$; $p < .001$). Thus, it can be concluded that the presentation of letters in a word context will improve performance over unrelated letter presentations. Further, comparing Figure 46 with Figure 49, it is apparent that modulations of 0.75 (24 cd/m^2) will obliterate the adverse effects of decreasing character size at least as well as 0.90 modulation (66 cd/m^2) does for noncontextual material. At a modulation of 0.38 (8 cd/m^2) or less, the beneficial effects of a character size greater than 17 min will become of significance to the designer of contextual displays.

The difference-score data are generally consistent with the expectations indicated previously. As character size decreases, the difference scores become larger; that is, words are providing the greatest advantage at the smaller character sizes. The highest level of luminance compensates for reduced character size and thus keeps the anagram scores high enough to diminish this difference at the smallest angular subtense.

While it is felt that the experimental procedure and results have been fruitful, it would have been desirable to shorten the tachistoscopic presentation time. The performance for all subjects under the word presentations was close enough to the maximum possible score that the true shape of the character-size-by-luminance response surface for words may be somewhat obscured. If the word-score range were attenuated in this manner, the difference scores would be of doubtful meaning. For that reason, less reliance has been placed on the difference-score analysis than was originally intended.

Evaluation of the spatial frequency analysis. Due to a lack of literature concerning spatial frequency analysis of discrete characters such as letters, the approach used in this research was selected largely due to compatibility with previous research in this laboratory on continuous images. The concepts of spatial frequency analysis are readily applied to the point configurations, but the spatial frequency constituted by the letter size and font is not as easily handled. Proceeding in a sequential, and hopefully logical manner, an attempt was made to correlate just those spatial frequencies obtained from the power spectra of individual points.

It is anticipated that innovative scanning methods, a more relevant Fourier analysis technique, or some combination of these two, would better predict dot-matrix sensitivity. This is investigated in Sections V, VI, and IX.

Conclusions

While it was demonstrated that the spatial frequency of individual dot-matrix cells does not constitute the basis for performance prediction when taken alone, it is feasible to predict intelligibility of noncontextual letters through existing Fourier methods. This prediction can be made by means of photometric scans of the individual point configurations. Correlations above $r = 0.80$ can be expected for those analyses which utilize weighted log-log transfer function area as a predictor. The choice of vertical angular subtense as a weighting factor is not ideal, but it demonstrates one approach which might be developed to provide a higher degree of prediction.

It was also shown that the performance increment experienced with the use of letters in context is more critical at diminishing character size and luminance than under more favorable viewing conditions. With noncontextual material, a modulation in excess of 0.90 is required to cancel the degraded performance encountered with characters which subtend 15 min to 17 min. However, with letters used in context, modulations of 0.75 will serve to maintain performance with letters subtending 15 min at a level not significantly different from letters subtending 31 min.

V. PREDICTION OF INFORMATION TRANSFER FROM SIMULATED SOLID STATE DISPLAYS

Introduction

Earlier sections of this report have summarized the effects of various dot-matrix design variables upon operator performance. Clearly, one might perform a very large number of such experiments to generate a catalog of such relationships from which one could deduce likely predictions for still undeveloped display designs. Such an approach is unsatisfactory, however, in that it is inductive in nature, never combining together all available information in a useful, quantitative, predictive model or expression.

Snyder (1973) has demonstrated the utility of a unitary metric concept of image quality. With such a unitary metric, that varies predictably with the critical design variables and also validly predicts operator performance, one can estimate performance to be obtained with futuristic design concepts prior to their fabrication. In this and the next section of this report, we shall present the results of two further experiments designed to produce predictive equations of information transfer. In that they consider a wide variety of design variables, they are more comprehensive than the study presented in Section IV.

The objective of the research described in this section is to utilize multiple stepwise regression techniques to derive predictive equations which reliably predict observer performance on representative tasks with dot-matrix displays. The display parameters used in these predictive equations are obtained by Fourier analysis of microphotometric scans of each combination of experimental variables.

In addition to developing a quantitative relationship between dot-matrix parameters and observer performance, this research refines the methodology of scanning microphotometry and Fourier analysis of sampled intensity distributions. Both the experimental results and the refinements in methodology thereby add to the body of useful literature concerning dot-matrix display symbology.

Method

This study was done in two contiguous segments. The first experimental phase yielded observer performance and photometric data from which predictive metrics for three separate tasks were obtained. The second phase of this research attempted to provide some degree of predictive validity for the metrics obtained in the previous segment. Each phase of the research constitutes a distinct experimental effort. However, both phases of the experiment utilized common equipment, procedures, and experimental measures.

Experimental design. Since a predictive function should be fairly generalizable to many types of displays, a rather wide range of within-character parameters was used in the first experimental phase. A completely factorial design in which three shapes, three center-to-center dot spacings, three dot sizes, and two levels of luminance contrast were combined was employed for this stage of the research. The actual levels of these variables are reported in Section III.

For the verification phase of the research, three displays built by commercial manufacturers were simulated in as much detail as possible. The three displays chosen were the Burrough's "SELF-SCAN II," the Owens-Illinois "DIGIVUE," and the prototype Westinghouse "TFT" (thin-film transistor). Due to limitations imposed by the Tektronix 4014-1 display which was used in this research, it was not possible to simulate the actual size of the display elements for the displays mentioned above. Accordingly, the sizes of the dots which comprise these displays were scaled up to allow shape definition, and the viewing distance was lengthened appropriately. Thus, in this phase of the experiment, the DIGIVUE simulation was viewed from 204 cm, while the SELF-SCAN and TFT were viewed from 102 cm. It should be noted that all displays used in the initial phase (Section III) were viewed from 102 cm.

With minor exceptions, the performance data collection procedure for the verification phase was identical to the initial experimental stage. It has already been noted that the viewing distance for the DIGIVUE was greater than that used in the initial experiment. The headrest used to fix viewing distance was difficult to move the required extra 102 cm. This forced the experiment to be blocked by display type. Subjects were randomly assigned within these blocks. The block number was assigned on a first-come-first-served basis and was thus dependent upon the subject's scheduled run date. Only one level of ambient illuminance, 5.4 lx, was used for all display-matrix size combinations.

All the characters used in the initial phase of the research were comprised of a dot matrix which was 5 dots wide and 7 dots high. In the verification phase, matrix size was the other independent variable. The three sizes used were 5 × 7, 7 × 9, and 9 × 11. The complete experimental design for the verification experiment is shown in Figure 60. The font was constant throughout the experiment and was based on our study of 5 × 7 dot-matrix fonts, as reported in Section VII. For the larger matrix sizes, the 5 × 7 font was scaled up as necessary due to the availability of more dots per character, but the general font "style" remained unchanged. All display type and matrix size combinations are shown in Figures 61 through 69.

Observer tasks. The actual performance data collection procedure and analysis of results for the first phase of the experiment were described in detail in Section III. However, it is worthwhile to note again the response measures which comprised the performance data for this study, since both phases of the experiment utilized the same three measures. These measures were (1) differential reading speed, (2) time to locate the target in a structured search, and (3) time to locate the target in a random, unstructured search. These three measures (or tasks) are representative of the types of activities engaged in by actual users of computer-generated displays.

Apparatus. The actual shapes, sizes, and spacings of the simulated display elements for the verification study are indicated in Figure 70. The shapes are shown as straight-edged geometric figures for purposes of clarity. It must be noted, however, that the Tektronix display upon

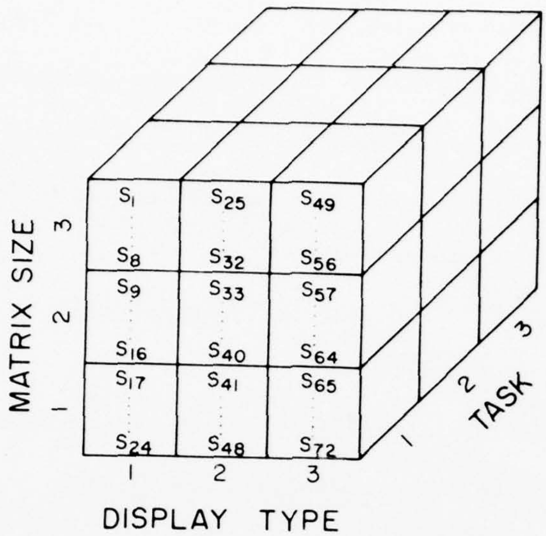


Figure 60. Experimental Design

Figure 61. DIGIVUE Simulation, 5 × 7 Matrix Size

Figure 62. DIGIVUE Simulation, 7 × 9 Matrix Size

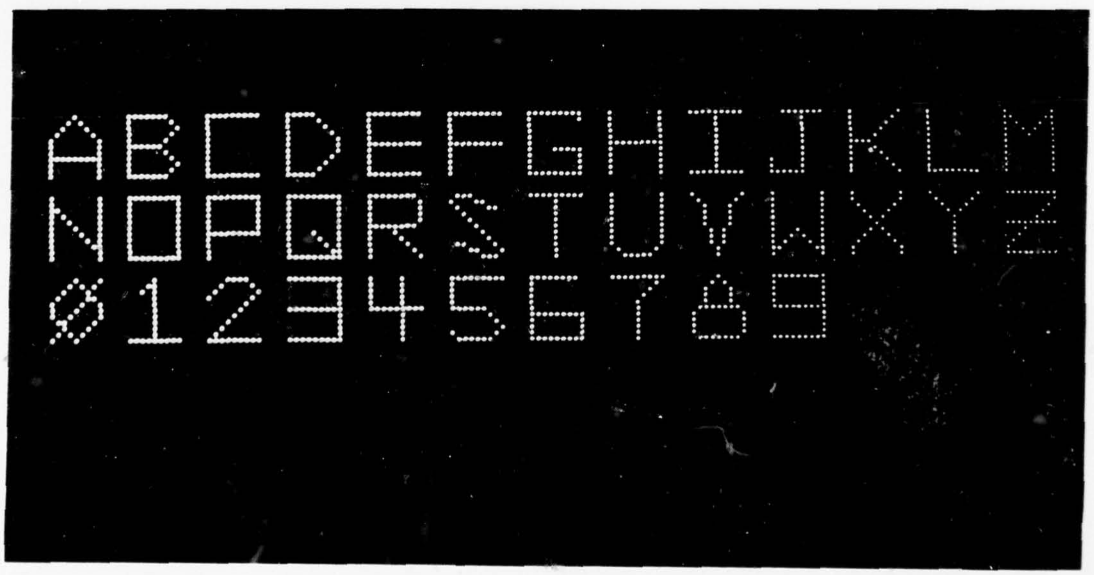


Figure 63. DIGIVUE Simulation, 9 × 11 Matrix Size

Figure 64. SELF-SCAN Simulation, 5 × 7 Matrix Size

Figure 65. SELF-SCAN Simulation, 7 × 9 Matrix Size

Figure 66. SELF-SCAN Simulation, 9 × 11 Matrix Size

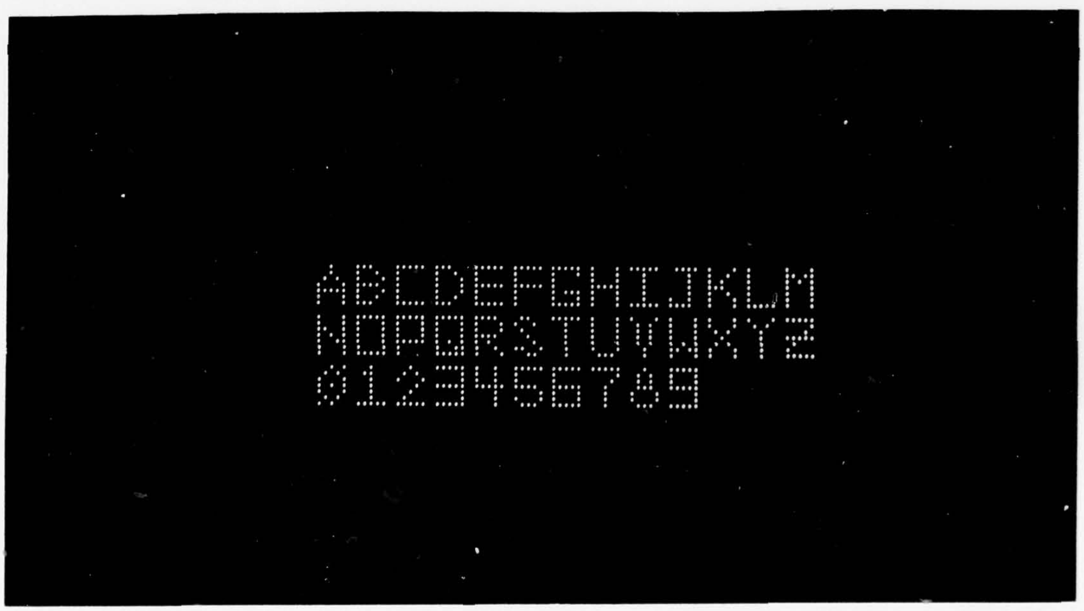


Figure 67. TFT Simulation, 5 × 7 Matrix Size

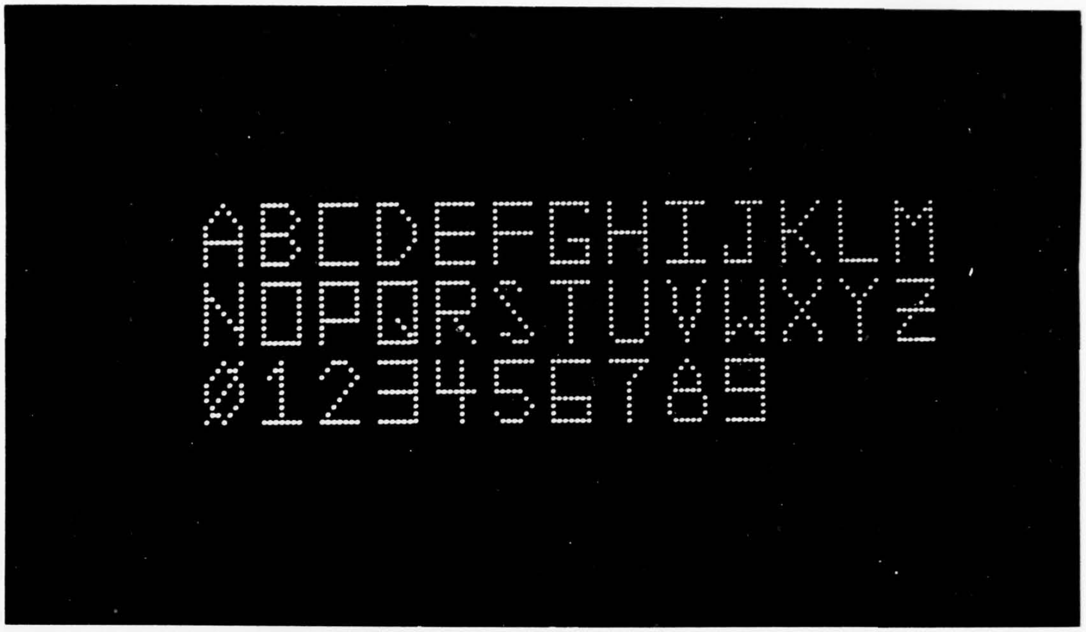


Figure 68. TFT Simulation, 7 × 9 Matrix Size

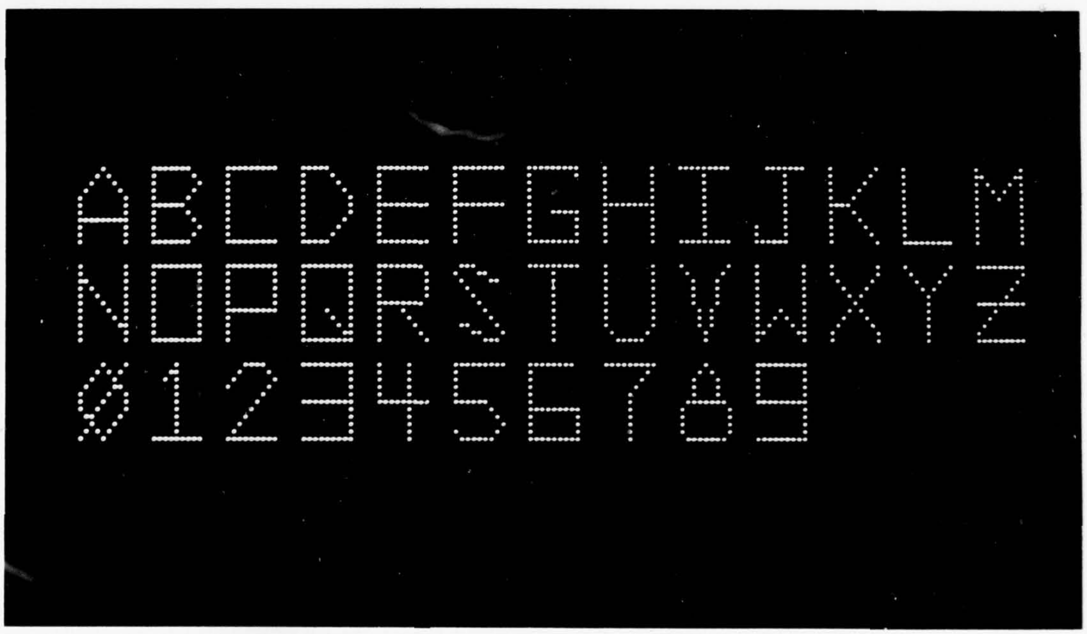
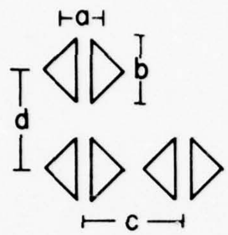


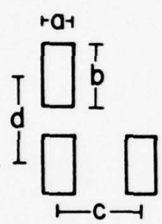
Figure 69. TFT Simulation, 9 × 11 Matrix Size

DIGIVUE



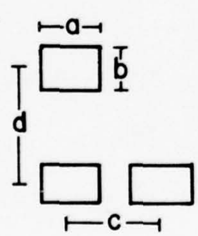
a=.813mm
b=1.240mm
c=1.697mm
d=1.697 mm
VIEWING DISTANCE=
203.2cm

SELF SCAN



a=.610 mm
b=1.067mm
c=1.554 mm
d=1.554mm
VIEWING DISTANCE=
101.6cm

TFT



a=.813 mm
b=1.118mm
c=1.600mm
d=2.083mm
VIEWING DISTANCE=
101.6cm

Figure 70. Simulated Dot Parameters

which experimental presentations were made is subject to slight blooming, which tends to round the edges and alter the orientation. The shapes shown are the approximate shapes of what will be referred to as "dots" in this study.

All photometric measurements for this research were done with a Gamma Scientific Model 2400 Digital Photometer. Scanning across sections of the CRT was accomplished by having the computer engage and disengage a scanning eyepiece drive made by Gamma Scientific. Prior to all measurements, the photometer was calibrated to 100 foot-Lamberts (343 cd/m^2) with a Gamma Scientific Model 220 Standard Lamp Source. The Tektronix 4014-1 display has been previously described.

Photometry. The method used to acquire photometric data was identical for both phases of this research. Since the purpose of this entire study is to relate quantitative, i.e., photometric, information to observer performance, the photometric procedure will be described in some detail.

The main pieces of the photometer are the eyepiece, where all focusing, magnification, and scanning take place; the photomultiplier (PM) tube, which is connected to the eyepiece by a fiber optic cable; and the digital readout unit, which is electrically connected to the PM tube.

The eyepiece used in this research was a scanning type with a slit input stage. The slit integrates intensity over its area much as the human eye does. This slit is oriented perpendicular to the direction of scan and is approximately 25 microns wide by 2500 microns long. The scanning eyepiece moves the slit input stage 10 mm in the image plane. The corresponding distance in the object plane (display face) depends on the magnification of the objective lens used. All scans for this research were done with a nominal 1× objective, thereby achieving 10 mm long scans in the object (CRT) space.

After calibration of the photometer by the 100 ft-L source, all computer connections were made and checked. In addition to the three main photometer components, several other pieces of equipment had to be added to allow computer control and acquisition capability. All these components and interconnections are shown schematically in Figure 71.

From the digital readout unit, the conditioned PM signal was routed through an operational amplifier. This amplifier changes the unipolar output of the photometer to a bipolar (±5 volts) signal which is compatible with the analog front end (LPS-11) of the computer. A power supply was used in place of batteries for the scanning motor. This power supply voltage was routed through a relay which was controlled by the computer. A voltage was also taken from this power supply to signal the computer program that a scan should be taken.

When a "go" signal was sent to the computer, the scanning drive relay was closed for exactly 60 s. The voltage of the power supply was set so that the scanning slit traversed 10 ±0.05 mm in that 60-s period, during which the analog front end of the computer was sampling the output of the photometer (through the operational amplifier). This sampling was done at a frequency of 100 Hz and the data were stored on magnetic tape. At the end of a scan, a file containing

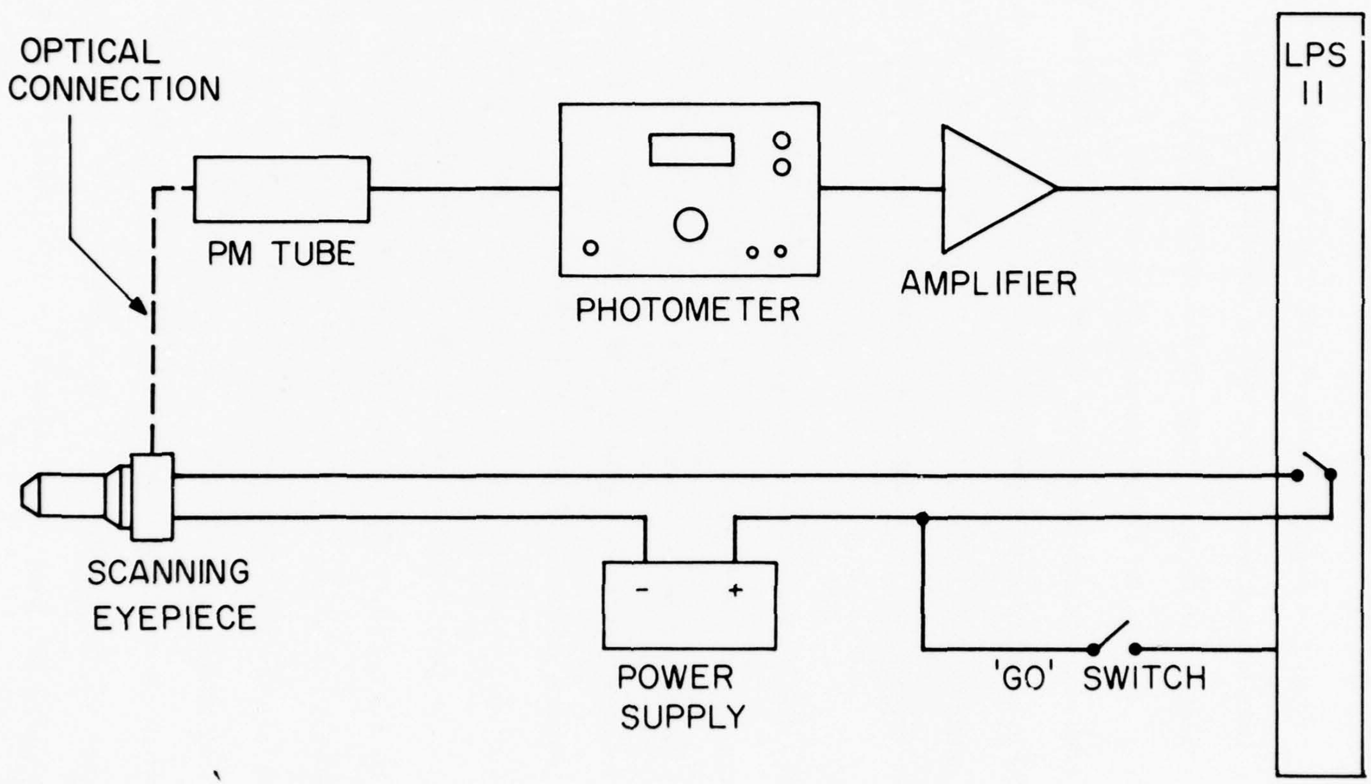


Figure 71. Schematic of Photometer Interconnects

6000 data points taken at equally spaced intervals in time and space existed on magnetic tape.

Such a scan was taken both vertically and horizontally for every size, shape, spacing, and illuminance combination used in both phases of this research. What the eyepiece actually scanned was a row (or column) of dots (pseudopoints) from each experimental condition. Thus, for the first phase there were 104 scans required, and for the second phase there were 6 scans.

Analysis of photometric data. It was noted previously that the primary quantities of interest are related to the spatial frequency and intensity content of the display. The photometric scans described in the last section produce files on magnetic tape which contain the converted luminance values at certain discrete points on the display. The method used to analyze the spatial frequency content of these scans was numerical Fourier analysis. The IBM routine FORIT was used to calculate a given number of Fourier coefficients for any scan (FORIT, 1970). This routine assumes that the input to it is a tabulated periodic function with an integral number of cycles in an array. The requirement of integral cycle input mandated the use of an optimization routine to select the correct number of points as input to FORIT.

The optimization routine developed for this research was necessary because few, if any, actual photometric scans contained an exact integral number of cycles of periodic dot information. It was not practical, due to the amount of time required, to simply delete one point at a time until an integral cycle point was located. A flow chart of this optimization routine is shown in Figure 72.

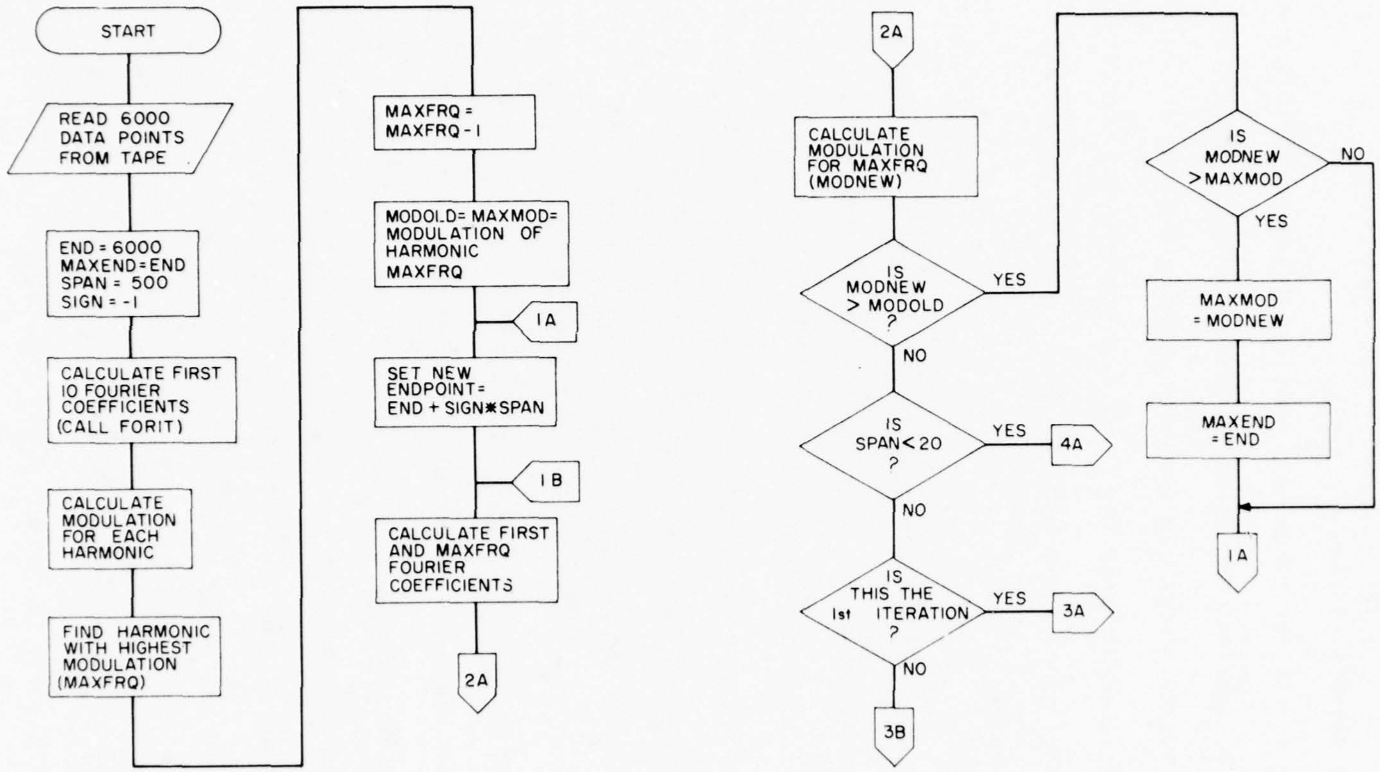


Figure 72. Flow Chart of Optimization Routine

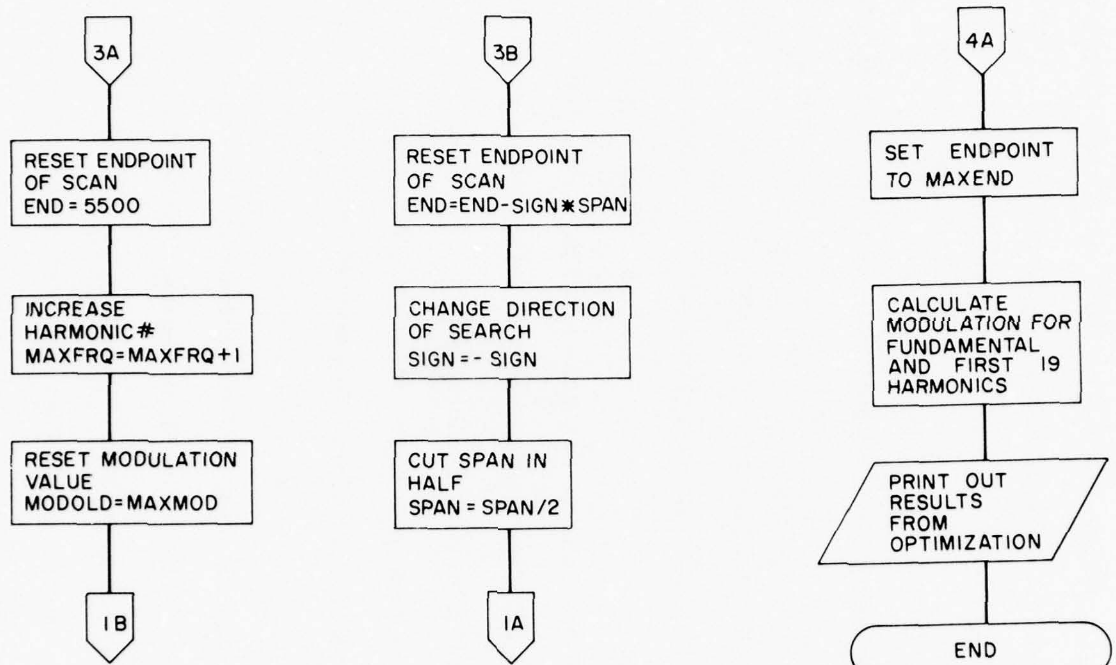


Figure 72--*Continued*

It can be seen that the criterion used for search direction reversals was the modulation of the fundamental spatial frequency of interest. It has been shown that the modulation of any spatial frequency can be calculated as the power at that frequency divided by the average intensity of the scan (Keesee, 1975). There are two assumptions made in this optimization routine. First, at least two cycles of the function must be present in the scan. This is necessary because the search routine can only eliminate points from the scan, not add points to it. If fewer than two cycles were present, it is probable that the routine in its present form would attempt to optimize at zero cycles. Second, the optimization procedure assumes that a local maximum is also the global maximum. This assumption is met by the nature of the Fourier analysis routine, i.e., the power of a given frequency has only one maximum in the neighborhood of an integral number of cycles of that frequency.

Once the scan data were trimmed to the appropriate number of points, the modulation of the fundamental and the first 19 harmonics were calculated. This procedure provided, for each scan, the fundamental spatial frequency and the modulation associated with it and with each of its first 19 harmonics. These data were then used to calculate other quantities of interest. Using the threshold detectability curves of DePalma and Lowry (1962) for sine-wave intensity distributions, a pseudo-MTFA was calculated for each scan. This calculation was begun by determining the crossover frequency relative to the detectability curve. Then, the area between the display modulation and detectability curves was calculated using numerical straight-line integration. The resulting area is referred to as a "pseudo" MTFA because the display modualtion curve is not a transfer function, but rather the modulation of frequencies derived by a specific mathematical technique.

In addition to the pseudo-MTFA, several other scan-related constants were produced by this routine. Two such quantities were used in later analyses, namely, the crossover frequency and the frequency range, i.e., the distance in cycles/degree from the fundamental to the crossover.

Derivation of the metric equations. After the photometric values were obtained, scatter plots of these variables with the dependent observer performance variable for each task were generated. This was done to visualize what effect any transformations of variables would have. Since there is no ideal method for choosing proper predictor variables for empirical curve fitting, variables were selected which, on the basis of past and present research, should account for reasonable proportions of measured variance. In addition to research-based variables, variables transformed to fit observed data patterns are often used.

Using both approaches, a total of 20 variables was eventually used as a pool of regression predictor variables. These 20 variables were divided between vertical and horizontal terms. All predictor variables used are listed and defined in Table 25.

The actual regression analysis performed on these data was the Stepwise Multiple Regression (SMR) procedure as implemented in the

Statistical Analysis System, Release 76.4 (Barr, Goodnight, Sall, and Helwig, 1976). In essence, the SMR procedure produces an equation of the form $Y = a + bX_1 + cX_2 + \ldots + \Theta X_n$, where $X_1, \ldots, X_n$ are independent variables and b, . . . , Θ are the least-squares coefficients for the independent variables. Y is the dependent variable and "a" is the y-intercept of the equation.

TABLE 25. Pool of Predictor Variables

Vertical	*Horizontal*	*Description*
VFREQ	HFREQ	Fundamental spatial frequency (cyc/deg)
VFLOG	HFLOG	Base 10 log of fundamental spatial frequency
VSQR	HSQR	Square of (fundamental spatial frequency minus 14.0)
VMOD	HMOD	Modulation of fundamental spatial frequency
VDIV	HDIV	Fundamental spatial frequency divided by modulation
VLOG	HLOG	Base 10 log of VDIV and HDIV
VMTFA	HMTFA	Pseudo-modulation transfer function area
VMLOG	HMLOG	Base 10 log of VMTFA and HMTFA
VCROS	HCROS	Spatial frequency at which modulation curve crosses the threshold curve
VRANG	HRANG	Crossover frequency minus fundamental frequency

The procedure starts with a dependent variable and a pool of predictor variables. The dependent variable is evaluated at many points in the measurement space of the predictor variables. One predictor variable at a time is entered into the regression model. As each variable is entered, a partial sum of squares corresponding to the amount of observed variance accounted for by that variable is computed. In addition, the proportion of variance (R^2) accounted for by the entire regression model is computed. Utilizing the remaining (residual) variance as an error term, an F-ratio and significance level are calculated for each term in the model.

Since the predictor variables may not be independent of each other (orthogonal), the entry of a variable into the model may cause other variables already in the model to lose significance, even if the model as a whole accounts for more variance than at the last step. The level of significance for entry into and exit from the model can be set by the programmer. When no variable can enter the model at a given significance level, the procedure halts.

The major problem with this procedure is that, due to non-orthogonality of the predictor variables, a simple stepwise regression might halt when a certain combination of remaining variables might all be significant if entered together. In an attempt to bypass this shortcoming, SAS allows variables to be entered on the basis of increasing R^2, the proportion of variance accounted for by the entire model, without regard to individual significance levels. This approach allows the program to find the best n-variable model, from $n = 1$ to the total number of variables in the pool, one step at a time.

In this research, both the simple SMR procedure and the regression based on R^2, known in SAS as MINR, were used. The dependent and predictor variables were evaluated at 54 separate points in the measurement space. These points are from the 3 × 3 × 3 × 2 experimental conditions of Section III.

Correction for matrix size. In the first experimental phase, all characters were constructed with 5 × 7 dot matrices. In the verification experiment, all three common matrix sizes (5 × 7, 7 × 9, 9 × 11) were combined factorially with the other experimental variables. Obviously, the metrics derived from the initial performance data are valid for the 5 × 7 matrices only. By including matrix size as a variable in the second experiment, it was thought that the presence and extent of any performance variation with matrix size could be observed.

The method by which matrix size corrections were made was a simple linear regression on the mean performance times for tasks which showed a significant matrix size effect. If a significant effect was present, a multiple comparison analysis was done to ascertain the locus of the effect.

Results

Predictive metrics from phase one. Using the SMR procedures outlined in the previous section, three metrics (equations) were derived to predict the observer performance data obtained in the first experimental phase. These metrics are presented in Table 26, along with the proportion of observed variance accounted for by that particular model (R^2), the maximum R^2 if all variables are entered into the model, and the correlation coefficient of that model with the observed data (R).

TABLE 26. Predictive Equations

Task	*Metric and Related Information*
Tinker SOR	Adjusted Reading Time (s) = 1.43 + 0.023 (VSQR) + 0.364(HMTFA) + 0.221 (VMTFA) - 4.825(HMLOG)
	Correlation Coefficient R = 0.76
	R^2 = 0.573
	Asymptotic R^2 = 0.70
Menu Search	Search Time (s) = 0.78 + 0.024(VSQR) + 2.72(HLOG) + 0.193(VMTFA)
	Correlation Coefficient R = 0.69
	R^2 = 0.471
	Asymptotic R^2 = 0.59
Random Search	Search Time (s) = -48.50 - 138.49(HFLOG) + 192.89(VFLOG) - 0.642(HMFTA) - 0.734(HSQR) + 0.982(VSQR) - 0.043(HDIV)
	Correlation Coefficient R = 0.71
	R^2 = 0.499
	Asymptotic R^2 = 0.60

It is a rather arbitrary decision as to the number of terms to include in a predictive model. There is no satisfactory method available to determine when one step increase in R^2 ceases to be significantly different from the previous step. This situation exists because of the nature of the regression procedure itself and the non-orthogonality of the predictor variables. The SMR procedure keeps adding and deleting terms on a step-by-step basis. Thus, from one step to another both the degrees of freedom as well as the individual model components, and the within-model variance, can change. The methods which exist for testing the significance of changes in R^2 assume independent determinations of this value. Obviously, the variance accounted for from step to step in the SMR procedure is not independent.

Generally, continued addition of terms to a regression model will result in a continued increase in the proportion of predicted variance. Usually, there is a point beyond which addition of more terms will result in smaller and smaller increments in R^2. One method used to find a stopping point is to continue adding variables to a model until an apparent asymptote is found for R^2. The asymptote in the present research is the R^2 obtained with all predictor variables in the solution. The model is then taken which, with the fewest significant terms, accounts for a reasonably large part of the asymptotic value. This method was used by Keesee (1975) to derive metrics for raster scanned threshold detectability curves. Virtually the same method was used in this research to decide on a cutoff point for all three models. The asymptotes for R^2 are shown, along with the metrics, in Table 25. The detailed results of the regression analysis are presented in Appendix C.

Phase two verification. The analysis of variance data from the Tinker SOR Test showed a statistically significant effect due to matrix size ($p < .05$) and a significant interaction between matrix size and element shape ($p < .05$). These results are summarized in Table 27. The main effect of matrix size is shown graphically in Figure 73. A Newman-Keuls analysis showed the 5×7 matrix to be significantly better

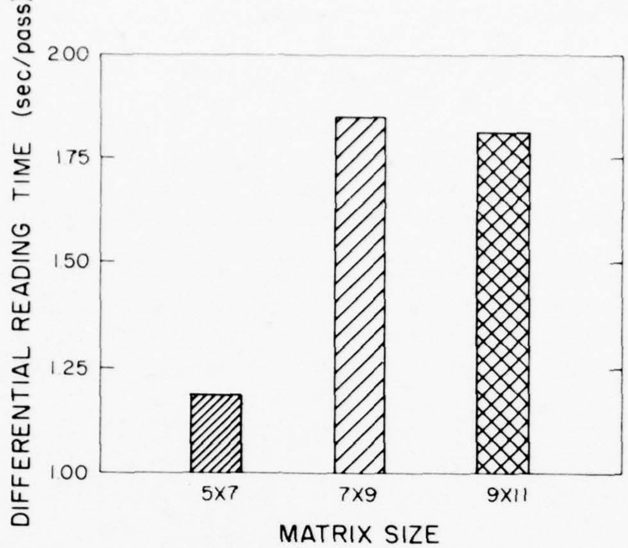


Figure 73. Effect of Matrix Size upon Reading Time

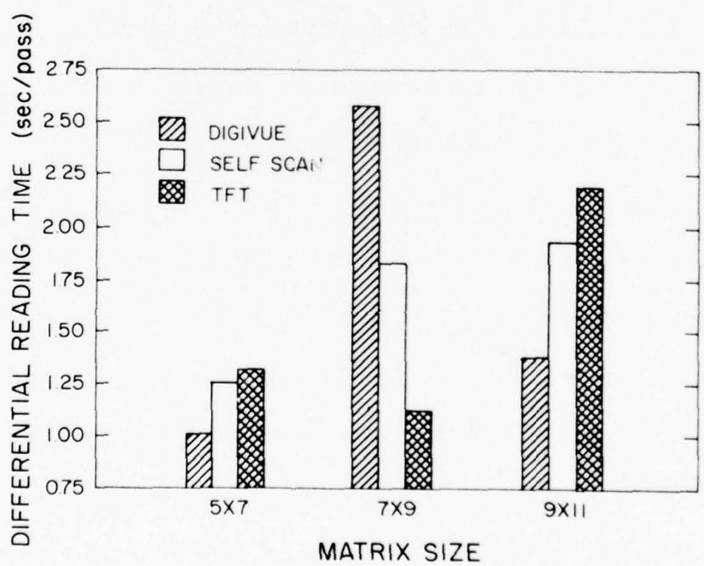


Figure 74. Effect of Matrix Size by Dot Shape Interaction upon Reading Time

than either the 7×9 or 9×11 matrices ($p < .01$). Adjusted mean reading times for the 7×9 and 9×11 matrices were not significantly different ($p > .05$).

TABLE 27. Analysis of Variance Summary for Tinker SOR Task

Source of Variance	*df*	*MS*	*F*
Matrix Size (*M*)	2	3.418	3.28[a]
Dot Shape (*S*)	2	0.124	0.12
$M \times S$	4	2.813	2.70[a]
Subjects within *M*,*S*	63	1.043	
Total	71		

[a] $p < .05$.

The matrix size by element shape interaction can be seen in Figure 74. A Newman-Keuls analysis showed no difference between element shapes for the 5×7 matrix ($p > .05$).

For the 7×9 matrix size, the TFT was significantly better than either the SELF-SCAN or the DIGIVUE ($p < .01$). In addition, the SELF-SCAN proved to be superior to the DIGIVUE at this size ($p < .01$).

For the largest matrix size, 9×11, the DIGIVUE was significantly better than either the SELF-SCAN or the TFT ($p < .01$). The SELF-SCAN and TFT showed no significant difference in performance ($p > .05$).

Analysis of data from the menu search task showed a highly significant effect due to matrix size ($p < .006$). The results of this analysis are summarized in Table 28. The significant matrix size main effect is shown graphically in Figure 75. A Newman-Keuls analysis

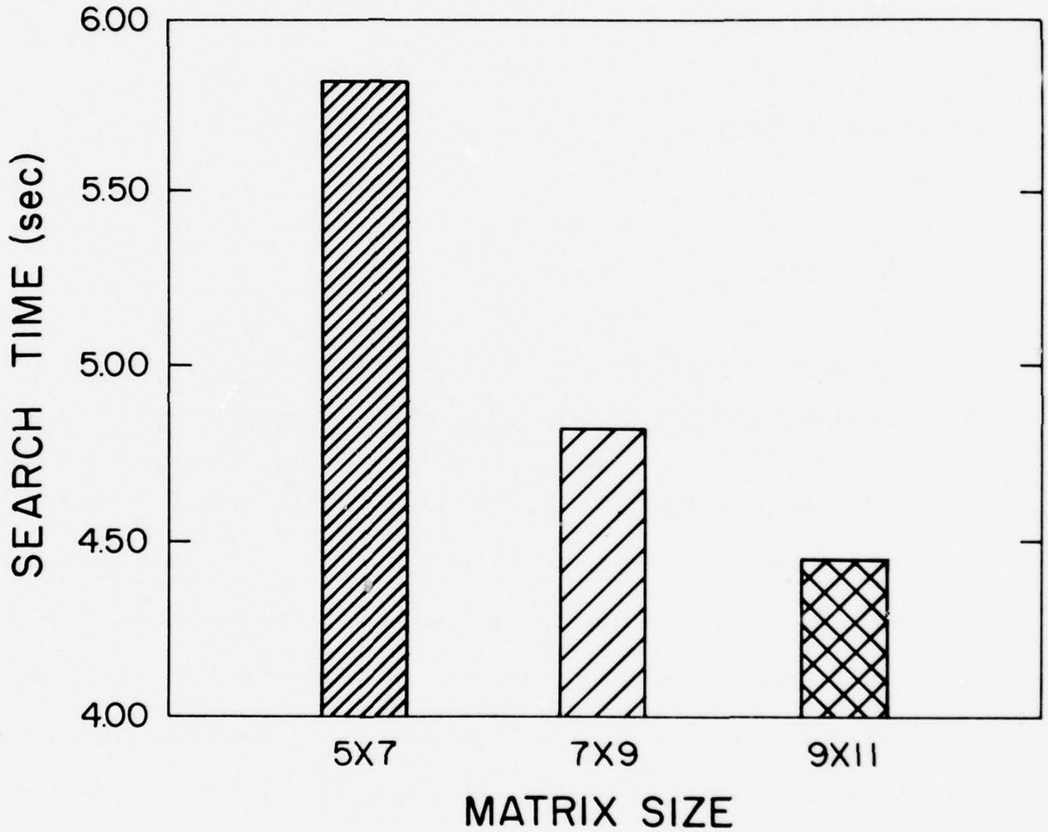


Figure 75. Effect of Matrix Size
upon Menu Search Time

showed the 9×11 matrix size to be superior to both the 7×9 and 5×7 matrices ($p < .01$). Also, the analysis revealed that the 7×9 matrix was significantly better than the 5×7 ($p < .01$).

TABLE 28. Analysis of Variance Summary for Menu Search Task

Source of Variance	*df*	*MS*	*F*
Matrix Size (*M*)	2	10.275	5.57[a]
Dot Shape (*S*)	2	0.227	0.12
$M \times S$	4	3.422	1.85
Subjects within *M*,*S*	63	1.846	
Total	71		

[a]$p < .006$.

Analysis of variance data from the random search task revealed no significant effects from matrix size, element shape, or their interaction.

Validation of metrics. The validity of the predictive metrics was also checked using the performance data from this part of the research. Utilizing the metrics described earlier and photometric data from the simulated display types, predicted performance means were calculated for each task. These were calculated from 5×7 matrices only, since the actual photometric values do not change with different matrix sizes. The predicted and observed performance measures are shown in Table 29.

Several things can be seen from the table of predicted versus actual data. The most obvious discrepancy between measured and predicted values occurs for the DIGIVUE simulation in all tasks. The probable explanation for this mismatch is that the fundamental spatial frequency for the DIGIVUE is approximately 22-23 c/deg. The range of spatial frequencies used in the regression procedure which yielded the predictive metrics was approximately 4-17 c/deg. The DIGIVUE elements are clearly out of this range and regression equations are quite unpredictable in such regions. The correlation between predicted and actual means for all three tasks and all three display types is 0.16, while the Spearman rank-order correlation between predicted and actual means, excluding the random search data, is 0.73.

TABLE 29. Predicted and Measured Performance Data (s)

Task	*Type*	*DIGIVUE*	*SELF-SCAN*	*TFT*
Tinker SOR	Predicted	3.08	1.40	1.71
	Measured	1.65	1.67	1.53
Menu Search	Predicted	8.15	4.53	5.89
	Measured	5.09	4.97	4.90
Random Search	Predicted	35.91	3.58	-11.78
	Measured	5.45	5.82	5.93

The other anomaly in the predicted data is the negative value predicted for the TFT random search measure. This type of task historically produces quite variable data, since the human performance is so dependent on individual factors such as search strategy and set. The original performance data used to derive the metric for random search had greater variance than the data from either of the other two tasks.

The instability of this metric can further be attributed to the asymmetry of the vertical and horizontal spatial frequencies in the simulated Westinghouse TFT display. The characters used in the first experimental phase were composed of dots with equal vertical and horizontal spacing. The predictive equation derived from these data is quite sensitive to departures from symmetry as seen from the large discrepancy between predicted and measured performance for the TFT display.

Discussion

Prediction metrics. The stated objective of this research is to derive metrics which validly predict observer performance on several typical tasks. In addition, these predictive equations were to be as compact as possible while utilizing variables which inherently contained information about many display-related parameters. To what extent has this research fulfilled these objectives?

The metrics derived in this study contain acceptably few terms which represent different quantitative elements of the displayed intensity distributions. The terms are broadly divided into horizontal and vertical categories. This dichotomy is logical from a physical standpoint, i.e., separate photometric scans were taken horizontally and vertically. The horizontal and vertical division is also predicated upon research which points to orientation sensitivity of the visual system.

Within the broad division of orientation, the predictor variable pool can be further defined in terms of spatial frequency, modulation, and a combination of both modulation and spatial frequency. In addition to these terms, transformations of raw terms are also included in the metrics, i.e., logarithmic and quadratic equations. Such transformations have been found useful in predicting observer performance in a number of visual research studies (Albert, 1975; DePalma and Lowry, 1963); hence, their inclusion in the regression models is a logical extension of previous work.

Generally, the predictor variables included in the derived metrics appear to be appropriate both in terms of the stated objectives of the research and as an extension of the work done by many investigators on several display-related parameters. The variables are elegant in that they contain information from many separate dot-matrix characteristics previously studied in isolation, e.g., dot size, dot shape, dot spacing, and luminance contrast.

The predictive metrics are relatively simple, account for a substantial proportion of observed variance, and, subject to the constraints of the original data, have been shown to be fairly valid predictors of observer performance. The predictive validity of these metrics should be viewed in the framework of the current state of knowledge about the variability of certain tasks as well as the intended use of such metrics.

Predictive equations such as those derived in this study are meant to be used to predict relative observer performance rather than absolute performance. That is, when a number of displays with different image-related parameters are compared, the predictor should allow a rank ordering of these displays with respect to observer performance on specific types of tasks. The equations are not intended to be used to calculate absolute performance on a given task with a given display, for such absolute performance is also affected by many additional, non-display-related variables.

Even with this restriction, the predictive metric derived for random search time has been shown to have poor predictive validity. In the light of previous research on this type of task, such low validity is not surprising. A large proportion of the observed variance in the performance data from Section III is accounted for by the random search prediction equation (R^2 = 0.499). The regression procedure used to derive the metric essentially maximized the amount of predicted variance. When the performance data are extremely variable, as in the random search task, equations derived from these data are less likely to reliably predict proportions of variance from samples of data other than the original sample. Much research has shown that when such metrics are applied to data other than those from which the metrics are derived, the predictive validity is quite low (cf., Greening, 1976).

In addition to the different tasks investigated in this research, another dimension of the displays was also varied, that is, matrix size. It has been shown in Section IV that certain correction factors related to matrix size can be included in predictive models to account for performance changes. However, there are certain fundamental problems, perhaps not obvious, which preclude using such general factors in the present study.

First, a correction factor incorporating some measure of matrix size, e.g., number of dots, character area, etc., implies that this correction occurs along a continuous dimension. In fact, matrix size is a discrete variable. In this investigation, three common matrix sizes were used. Interpolation between these sizes would not be a legitimate or meaningful procedure. Even if this problem were overcome, perhaps by using a discrete-valued correction factor, there remains the fact that the effect of matrix size on observer performance has been shown by the present research to be highly task-dependent.

Inspection of the analyses of variance for the Tinker SOR task and the menu search task reveals the nature of the task dependence of the matrix size effect. In the case of the Tinker SOR task, the 5 × 7 matrix produces significantly *faster* adjusted reading times than either of the two larger matrices. In the menu search task, the 5 × 7 matrix produces significantly *slower* search times than either of the two larger matrices. In this task, the 7 × 9 matrix produces significantly slower search times than the 9 × 11 matrix.

A possible explanation for the task-matrix size interaction lies in the nature of the tasks themselves. The Tinker reading task requires the observer to scan a number of lines of contextual information and then decide which word is not appropriate in the passage. Since the characters became larger as more dots were added, the area to be scanned became larger as well. It is reasonable to expect, therefore, that as long as the characters are large enough to be legible, smaller characters should result in faster reading times due to fewer required eye fixations.

The menu search task involves very different response requirements by the observer. The search area was kept relatively constant, regardless of character size. The search strategy employed by different subjects obviously varies. In general, however, the fewer eye fixations one has to make to locate the target, the faster the search will be. As the characters become smaller, the space between each pseudoword in the search list becomes larger and larger. The probability of an observer fixating on a blank area of the display increases as the blank area increases. In addition, the probability of being able to distinguish more than one pseudoword at a time decreases as the list elements become more widely spaced. As the characters become smaller and the search list items more dispersed, one would expect search times to increase as, indeed, they did. This interpretation is consistent with known eye movement scanning data (e.g., Snyder and Taylor, 1976).

Besides the obvious design dilemma that this task dependence implies, what can be said of the observer performance as it is related to matrix size? Perhaps the most conservative approach is to impose the structure of the raw performance mean values on the predictor equations. That is, the Tinker SOR data show the mean adjusted reading time for the 7×9 and 9×11 matrices to be about 1.5 times that of the 5×7 matrix. It is then appropriate to multiply the predictive metric by 1.5 when 7×9 or 9×11 matrices are used and to omit this multiplicative factor when 5×7 matrices are to be employed. By similar reasoning, the predictive metric for the menu search task can be adjusted by multiplying the raw (5×7) prediction by 0.8 when larger matrices are to be used.

While such correction factors could be used, their efficiency is dubious due to certain experimental procedures. All matrix sizes for each simulated element shape were viewed at the same distance. This produced a confounding of matrix size with subtended visual angle.

It is possible that the mean values associated with the raw data were affected by this confounding. In any case, the matrix correction factors should be used only as general trend corrections and not absolute and precise predictors. In the font study of Section VIII, this confounding between matrix size and character size will be evaluated further.

Photometry evaluation. Aside from the metrics themselves, some very interesting findings surfaced during their derivation. One of the most gratifying discoveries was a very high correlation (R = 0.99) between horizontal and vertical spatial frequency measurements. These measurements were made by scanning photometry, a method which has, in the past, been considered to have significant measurement error, on the order of 5%. Since the vertical and horizontal scans were made independently, the high correlation between the resulting measurements is considerable vindication for the photometric methodology and optimization analysis routine. It also supports the luminance and spatial stability of the generated displays.

In addition to the photometry, the method of mathematically treating the resulting data proved to be reliable and capable of handling the normal noise associated with photometric data. It is perhaps a small point, but nevertheless important, that the Fourier routine be capable of handling the high-frequency noise present in the scan data. This allows the retention of high-frequency (edge) information in the scanned intensity distribution. The rounding of edges caused by high-frequency filtering in the photometer is a major source of error when calculating spatial frequency content of an intensity distribution. The ability to accept the high-frequency data in the analysis routine allows the filtering to be bypassed at the photometer.

Summary and Conclusions

This study has demonstrated that it is possible to account for large proportions of experimental variance on visual performance tasks with relatively simple display-related parameters. The proportion of variance accounted for by the derived models ranged from 0.47 for the menu search model to 0.57 for the Tinker SOR model. The metrics presented in this section contain relatively few terms. The terms themselves inherently contain information about many display parameters usually treated as isolated from one another. For instance, the MTFA measure includes, among other information, relative dot size, dot shape, dot spacing, and luminance contrast.

The values predicted from the metrics have been shown to be well correlated with actual performance when the predictor variables are within the range of the original variables from which the metrics were derived. One exception to this is the random search metric, which is extremely sensitive to violation of variable range.

The corrections applied to the metrics to account for matrix size are rough approximations and reflect trends rather than extremely precise numerical predictions. The inconsistent effect of matrix size across display types, as well as the small number of validation points, precludes any precise weighting of results for different matrix sizes.

VI. VALIDATION OF PREDICTION EQUATIONS USING AC AND DC PLASMA PANELS

Introduction

The study reported in the previous section produced prediction equations for three different tasks--menu search, random search, and reading. Because this previous study used the Tektronix 4014-1 terminal to simulate three different display devices, it is desirable to validate these prediction equations by conducting the same experiment, using the same tasks, with the actual rather than simulated display devices.

Unfortunately, the TFT EL display was not available in a computer addressable form at the time this study was to be conducted. Instead, the three displays selected for this experiment were the DIGIVUE AC plasma panel and two versions of the Burroughs SELF-SCAN DC plasma panel. One version of the SELF-SCAN had generally round dots, while the other had square dots. The square dot SELF-SCAN was essentially that simulated in the previous experiment.

Because of the limitation of the SELF-SCAN panel size, it was not possible to present the random search display on either of the SELF-SCAN displays. Thus, this validation experiment resulted in performance data for two tasks (menu search and reading) on three displays (DIGIVUE and two SELF-SCANS).

Method

Subjects. Seventy-two subjects were run in this experiment, 36 male and 36 female. All subjects were tested using a Bausch and Lomb

Orthorater to assure that their visual acuity was at least 20/25 corrected with no gross visual defects. All subjects were paid for their participation.

Apparatus. The displays used in this experiment consisted of two SELF-SCAN II plasma panels and one DIGIVUE plasma panel. The SELF-SCAN II panels differed only in the shape of the dot elements. One panel was constructed with a round dot shadow mask while the other was built with a square dot mask. The DIGIVUE panel was a standard Owens-Illinois design with a plastic touch panel cover which tended to "smear" the dot structure on the screen.

The computer system was the same PDP 11/10, LPS-11 combination used in earlier experiments. The DIGIVUE panel was interfaced to the computer using ITL interface boards. The SELF-SCAN panels were interfaced using a specially built serial-to-parallel converter.

The experimental room included a standard height table upon which the displays were placed. Markings were made on the table surface to assure accurate and repeatable placement of each display in either of two viewing orientations.

Experimental design. The experimental design for this study is shown in block form in Figure 76. Each display is seen by a total of 24 subjects, 12 male and 12 female. Each subject received both the Tinker Speed of Reading task and the menu search task at each of two viewing angles, 90° and 45°. The order of presentation of viewing angles was counterbalanced so that half the subjects saw the 90° viewing angle first while the other half saw the 45° viewing angle first.

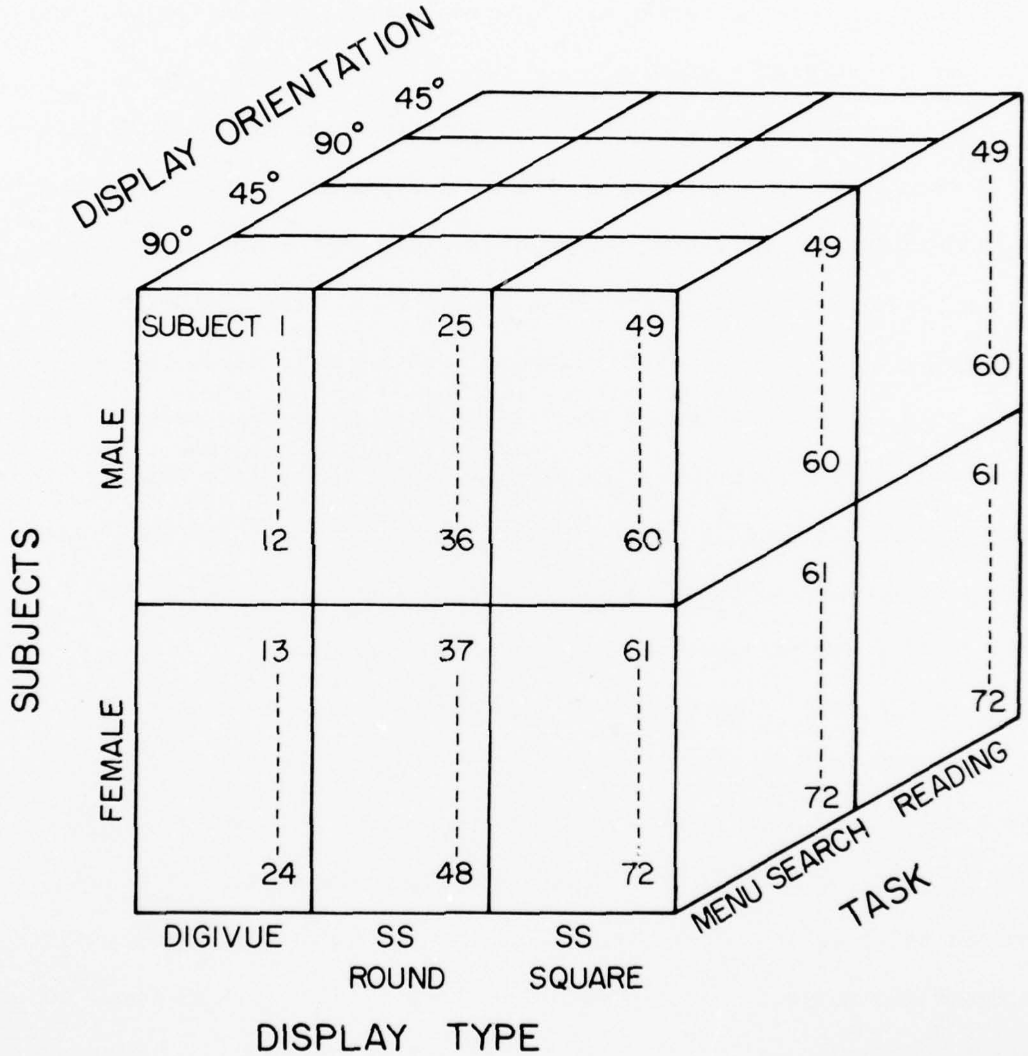


Figure 76. Experimental Design

Procedure. Subjects were seated before the display assigned to his or her block. Since display orientation was counterbalanced across subjects, half the subjects began the experiment with the 90° viewing angle and half with the 45° viewing angle. In either case, the display was placed so that the center was located approximately 61 cm from the plane of the subject's eyes.

The subjects were given a set of written instructions explaining the Tinker Speed of Reading test. These instructions stated that each passage to be seen on the screen contained one word which was not used in the context of the passage. When this word was found, the subjects were told to press a hand-held response button and to speak the out-of-place word. It was explained that an intercom located adjacent to the screen would be monitored by the experimenter to ascertain whether the correct word had been isolated. The subjects were also informed that, upon pressing the response button, the displayed passage would be erased and a new passage would appear in a short time.

At the conclusion of the written instructions, any questions posed by the subject were answered. The subject was told that the first few passages would be given for the purpose of practice. After this instruction period, the experimenter left the display room and retired to an adjacent computer room. Once situated, the experimenter informed the subject, via the intercom, that the trials were about to commence. The actual trials were controlled by the PDP 11/10 minicomputer. Ten practice trials and 25 experimental trials were administered at this time and the subject's responses were monitored via the intercom.

At the completion of the first Tinker trials, the experimenter reentered the display room and gave the subject a set of written instructions explaining the menu search task. These instructions described the nature of the menu search procedure, as was described in Section III of this report. Subjects were cautioned in the instructions to press the response button as soon as they found the target and to keep their eyes on the location where they found the target. They were informed that as soon as they pressed the button, the display would be erased and each potential target position would be numbered.

The subjects were asked to enter the number of the location of the target on a keyboard located in front of them. After this number was entered, the next trial would proceed. Again, any questions posed by the subject were answered and the experimenter withdrew to the computer room. The subject was informed that the trials were about to commence and the program was initiated. A total of five practice trials and twelve experimental trials were administered during this phase of the experiment.

After these two phases of the experiment were done, the experimenter reentered the display room and reoriented the display. The display was moved from the initial orientation to the other orientation.

After the viewing angle was changed, the subject was informed that the Tinker SOR test would be done again with different passages. The written instructions were not read a second time, but the subject was allowed to retain the instruction set for reference, if necessary.

The same procedure was followed as in the first part of the experiment for both the Tinker and menu search tasks.

After both phases of the experiment, the subject was given a sheet of paper containing 10 typewritten Tinker passages. The subjects were instructed to read each passage, find the incorrect word, and cross out the word with a pencil. The subject was timed on this task with a stopwatch and the average time per passage served as the baseline reading speed for each subject.

After this baseline procedure, the subjects were paid, thanked for their participation, and allowed to leave.

Photometric data. All photometric data from the three displays were gathered after the subjects had been run. The procedure for obtaining the data was identical for all three displays.

All photometric scans were taken with a Gamma Scientific Digital Photometer and the data were placed on magnetic tape. The scans were made by moving a photometric microscope with a 4× objective along the horizontal and vertical axes of the displays. A 25 × 2500-micron slit collection aperture was mounted on the microscope and the entire microscope was moved by a small AC gearmotor. The data collection procedure involved closing a computer-controlled relay which activated the motor for 60 seconds. While the motor moved the microscope, the output of the photometer was sampled at 100 Hz by an analog-to-digital converter, which is part of the computer system.

A total of 6000 points were thus collected on each scan and placed on magnetic tape. Several scans were taken horizontally and vertically at both 90° and 45° angles of view. Since the total distances traversed on each scan were slightly different due to motor voltage fluctuations, a Vernier scale attached to the microscope mount was read at the start and the conclusion of each scan and recorded on a data sheet.

After all scans were completed, they were subjected to digital Fourier analysis to determine the magnitude of the major spatial frequency components of each display in both vertical and horizontal axes, and at both perpendicular and oblique viewing angles. These data, and calculations made from these data, served as the independent variables in the previously derived performance prediction equations. The data analysis procedure and prediction equations were described in Section V.

Results

Menu search. The mean menu search time per subject per experimental condition was the basic datum used in an analysis of variance. As summarized in Table 30, both the display and orientation main effects were statistically significant ($p < .05$). The DIGIVUE display led to significantly longer menu search times than did either of the SELF-SCAN displays (Figure 77, $p < .01$). Further, the difference between the two SELF-SCAN displays was also statistically significant ($p < .01$), as determined by the Newman-Keuls multiple comparison test.

All three displays produced a significantly longer search time at the 45° orientation than when the subjects viewed the display at a normal 90° angle (Table 30, $p = .032$). The average time, across all three displays, was 4.20 s for the 90° orientation and 4.37 s for the 45° orientation.

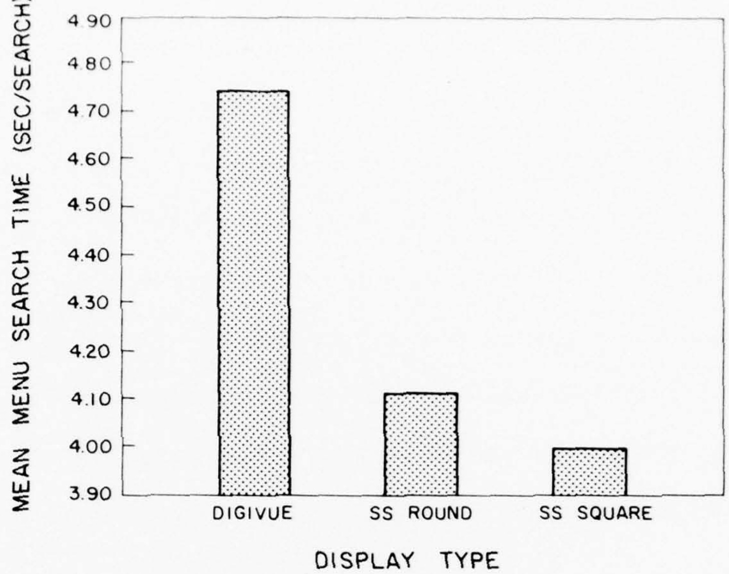


Figure 77. Effect of Display Type upon Menu Search Times

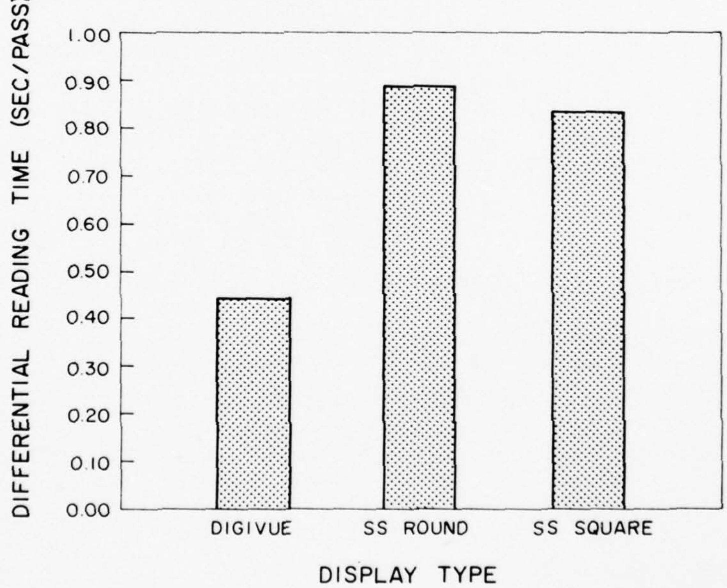


Figure 78. Effect of Display Type upon Corrected Reading Times

TABLE 30. Summary of Analysis of Variance of Menu Search Times

Source	*df*	*MS*	*F*	*p*
Display (D)	2	7.226	3.77	0.028
Sex (S)	1	2.402	1.25	0.268
Orientation (O)	1	1.095	4.80	0.032
D × S	2	1.860	0.97	0.386
D × O	2	0.082	0.36	0.699
S × O	1	0.059	0.26	0.612
D × S × O	2	0.080	0.35	0.705
Subjects within D,S (*S*s/D,S)	66	1.926		
O × *S*s/D,S	66	0.228		
Total	143			

Reading time. As in previous studies, reading times on the modified Tinker SOR test were analyzed, using the analysis of variance, for both corrected and uncorrected reading times, with the corrected times being the uncorrected time minus the baseline time as measured from the printed page SOR time score.

The summary of the analysis of variance of the uncorrected scores is given in Table 31, while the summary for the corrected scores is in Table 32.

For the uncorrected time scores, the only statistically significant (p = .013) result indicates that female subjects read more rapidly than males (6.10 *vs.* 7.12 s/passage). This is not surprising and merely verifies results achieved by numerous researchers dealing with verbal abilities.

TABLE 31. Summary of Analysis of Variance of Tinker SOR Scores

Source	*df*	*MS*	*F*	*p*
Display (D)	2	1.422	0.25	0.781
Sex (S)	1	37.383	6.51	0.013
Orientation (O)	1	0.125		
D × S	2	0.003	0.00	0.999
D × O	2	0.240	0.41	0.665
S × O	1	0.021	0.04	0.851
D × S × O	2	0.289	0.50	0.611
Subjects within D,S (*S*s/D,S)	66	5.739		
O × *S*s/D,S	66	0.583		
Total	143			

TABLE 32. Summary of Analysis of Variance of Corrected Tinker SOR Scores

Source	*df*	*MS*	*F*	*p*
Display (D)	2	2.995	3.13	0.050
Sex (S)	1	1.934	2.02	0.160
Orientation (O)	1	0.125	0.22	0.644
D × S	2	0.350	0.37	0.695
D × O	2	0.239	0.41	0.665
S × O	1	0.021	0.04	0.851
D × S × O	2	0.289	0.50	0.611
Subjects within D,S (*S*s/D,S)	66	0.958		
O × *S*s/D,S	66	0.583		
Total	143			

More importantly, Table 31 indicates that there was a significant (p = .05) display effect for the corrected SOR times. As illustrated in Figure 78, corrected reading times were significantly shorter (p < .01) for the DIGIVUE display than for either of the SELF-SCAN displays. Further, the square dot SELF-SCAN display produced faster reading times than did the round dot SELF-SCAN (p < .05), as indicated by the Newman-Keuls test.

Prediction of performance. The previous experiment, described in Section V, resulted in several measures of predicted performance from (1) geometrically shaped dots and (2) DIGIVUE and SELF-SCAN dots as simulated on a Tektronix 4014-1 display. Table 33 repeats these previous means, along with the performance means obtained in this experiment using the actual hardware.

TABLE 33. Comparison of Predicted, Simulated, and Final Performance Scores (seconds)

Performance Measure	*DIGIVUE*	*SELF-SCAN (square)*
Reading Time (corrected)		
Geometric Dots	3.08	1.40
Simulated Displays	1.65	1.67
Final Displays	0.43	0.89
Menu Search		
Geometric Dots	8.15	4.53
Simulated Displays	5.09	4.97
Final Displays	4.73	4.01

As seen from this table, the ordinal relationships between simulated and final scores are the same, although actual values deviate noticeably from predicted values.

Discussion

In a general sense, this study clearly validates the results of the DIGIVUE and SELF-SCAN display simulations. For the menu search task, the earlier prediction equations, the Tektronix display simulations, and these final actual hardware data all indicate that search time is shorter with the SELF-SCAN than with the DIGIVUE. Because the SELF-SCAN has 9.4 dots/cm and the DIGIVUE has 23.6 dots/cm, the characters are larger on the SELF-SCAN display. It is generally concluded that larger characters are more detectable in the visual periphery, thereby leading to more efficient search and reduced search times.

The absolute differences between the menu search times for the simulated and final DIGIVUE and SELF-SCAN displays is quite small (7% and 17%, respectively), a result which nicely supports the validity of the Tektronix simulation technique. This magnitude of difference is often found for different subject samples and need not necessarily be attributed to display variables.

For the reading task, the final scores deviate considerably from the simulated and predicted times. There are three reasons for these large differences. First, and as pointed out in Section V, the prediction equations had to be extrapolated for the DIGIVUE simulation because several of the photometric and geometric variables for the DIGIVUE lay outside the ranges of these variables in the previously developed prediction equations. Such extrapolation often leads to inaccurate prediction, and this is indicated by the large differences between the geometric prediction results and the simulated results, Table 32.

Secondly, the reading times in Table 32 are *corrected* reading times. For the simulated and geometric results, the correction was based upon the average time to read Tinker SOR passages displayed on the Tektronix terminal, but in a stroke character format. Thus, these corrected (or difference) scores take into account the readability of the SOR passages on the stroked Tektronix display.

For the "final" results, however, the correction was based upon reading time for a typed page containing SOR passages. Apparently, the readability of the typed passages was more similar to the SELF-SCAN and DIGIVUE displays, thereby yielding smaller corrected reading times. It should be noted that the small difference between the two displays is not very large for either the simulated (0.02 s) or final (0.46 s) displays, again supporting the validity of the simulation technique on the Tektronix display. With a different reading baseline measure, the final display data means might have been more similar to the simulated data means.

Thirdly, the DIGIVUE display used in this study had a touch panel overlay which tended to blur individual dots to some extent. While this blurring was visually noticeable, it became even more apparent when photometric scans were made of this display. The blurring was sufficient to virtually eliminate any interdot modulation, thereby reducing the dot-matrix character to nearly a continuous stroke character, decidedly different from the characters on the simulated DIGIVUE display.

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INFORMATION TRANSFER FROM COMPUTER-GENERATED DOT-MATRIX DISPLAY--ETC(U)
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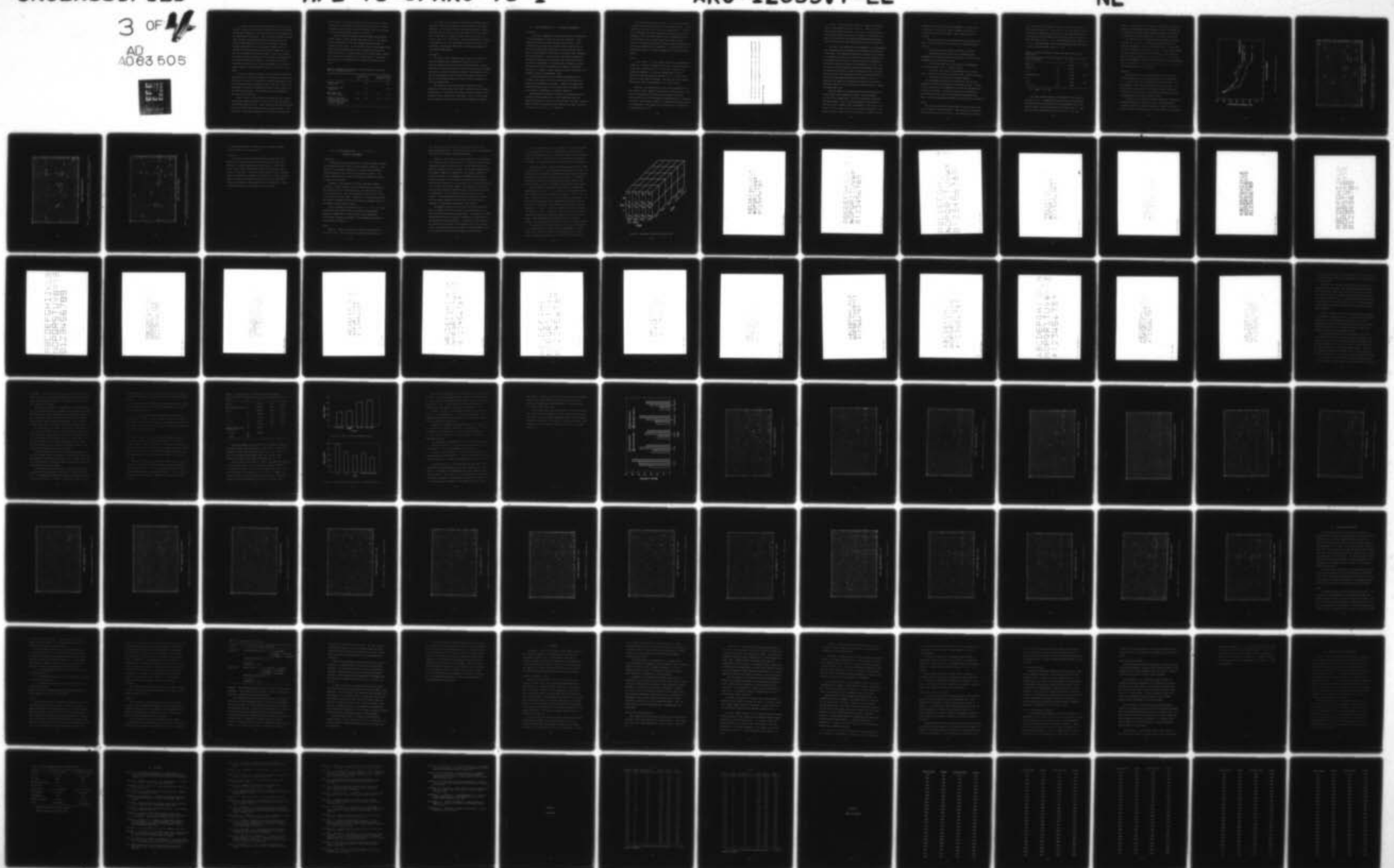

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It should be noted that both the simulated and actual displays indicate a longer reading time for the SELF-SCAN than for the DIGIVUE, although this difference is small and statistically nonsignificant for the simulated SELF-SCAN display. Such a difference should be expected, simply because a given Tinker passage requires more area on the 9.4 dot/cm SELF-SCAN than on the 23.6 dot/cm DIGIVUE. A passage occupying greater display area will generally require more eye fixations to read the passage, and thus greater reading time. The fact that the geometric dot predicted times are not in this ordinal relationship is again probably due to the inaccurate extrapolation of prediction variables for the DIGIVUE. This general result, that corrected Tinker SOR times are larger when passages are written with larger characters, was also reported reliably in Section III of this report.

At the 45° orientation position, both the DIGIVUE and SELF-SCAN displays emit less directional luminance, and thereby they display less contrast to the observer. Subjectively, the SELF-SCAN appears to have less contrast than does the DIGIVUE at the 45° position. However, the performance data showed no differential effect of display type on the two orientation positions. All three displays were degraded about the same at the 45° position.

Finally, there is one additional calculation that can be used to evaluate the simulation procedure as well as the prediction model for the SELF-SCAN square dot panel. (This could not be done for the DIGIVUE because of the dot blurring caused by the touch panel overlay.) This calculation is based upon a photometric scan of the actual SELF-SCAN panel, taken in the fashion indicated in Section V for the simulated SELF-SCAN. This photometric waveform, taken for both the 45° and 90° orientation, was then Fourier analyzed to obtain values to be inserted in the prediction equations (Table 26, Section V).

Table 34 indicates the menu search and reading times predicted for the square dot SELF-SCAN based upon these scans. It also repeats previous predicted times from the simulated SELF-SCAN display of Section V of this report. As seen from this table, the performance times predicted from these photometric scans are greater than the actual times by about 50% for the menu search and by a greater amount, probably due to the baseline reading task, for the reading test. In each case, they predict the 45° performance to be (logically) poorer than that at 90°.

TABLE 34. Comparison of Photometric Prediction Equation and Actual SELF-SCAN Performance Times (s)

	SOR Time		*Menu Search Time*	
	45°	*90°*	*45°*	*90°*
Geometric Prediction (Table 32)		1.40		4.53
Simulated SELF-SCAN (Table 32)		1.67		4.97
Final Study (with SELF-SCAN display)	0.73	0.93	4.07	3.94
Predicted, Final Study (using photometric scans from SELF-SCAN panel in Table 25 equations)	2.38	2.15	6.49	5.62

Of interest in this regard is the predicted performance from the photometric scans for the round SELF-SCAN as compared to the square SELF-SCAN. For the Tinker SOR test, the respective round *vs.* square predicted times are 2.63 *vs.* 2.15 (at 90°) and 2.47 *vs.* 2.38 (at 45°). For the menu search, the round *vs.* square times are 5.80 *vs.* 5.62 (at 90°) and 6.27 *vs.* 6.49 (at 45°). Thus, the predictions are similar to the empirical data: 90° performance is generally superior to 45° performance, and the square SELF-SCAN is on the average superior to the round SELF-SCAN display.

Conclusions

The result of this experiment clearly support the validity of both the Tektronix display simulation technique as well as the predictive equations for the menu search and reading tasks. Relative performance correlates well with the several variables studied, although some error in absolute performance is apparent. Based upon these data, one can feel moderately safe in applying the predictive equations of Table 25 to new display designs to estimate relative performance for search and reading tasks.

The results also reaffirm that larger characters are more appropriate for search tasks, while smaller characters lead to reduced reading times, a result which seems quite consistent and heuristically acceptable across several of our experiments. Thus, a display format may be optimal for one type of task and quite suboptimal for another.

VII. FONT OPTIMIZATION FOR 5 × 7 DOT-MATRIX ALPHANUMERICS

Introduction

It has been recognized for some time that certain characteristics of stroke alphanumerics affect their relative legibility. These characteristics have been gathered under the term "font." Much research has been undertaken to ascertain which stroke font is the most legible under certain conditions (cf. Cornog and Rose, 1967). Some of the more familiar stroke fonts are the Leroy, BUIC, Mackworth, and the Lincoln/Mitre. It has not been satisfactorily demonstrated in previous studies that the conclusions from stroke font research are directly transferrable to dot-matrix fonts, although two studies have indicated that the Lincoln/Mitre font, adapted to dot-matrix constraints, is superior to other commonly used fonts (Shurtleff, 1970; VanderKolk, Herman, and Hershberger, 1974).

The fonts developed for use by commercial manufacturers of dot-matrix display devices are, for the most part, not based on the meager body of knowledge on the subject. Indeed, most commercially available dot-matrix fonts seem to be based more on expediency than on any desire to standardize or to maximize legibility.

Manufacturers are generally consistent in the dimensions of the dot-matrix characters they utilize. Most commercially available displays use characters which are 5 dots wide and 7 dots high. A smaller number of displays, particularly those requiring both upper- and lower-case letters, use 7 × 9 or 9 × 11 characters.

The study reported in this section is the result of preliminary research on the general image quality of dot-matrix displays. In this experiment, the objective was to select one particular 5 × 7 font for use in subsequent experiments which would investigate other display parameters. Previous studies pointed to the Lincoln/Mitre font as the most legible, but it was felt that these studies were not conclusive. The present experiment compared two newly designed fonts and the Lincoln/Mitre font for legibility. The task utilized was the forced identification of a single alphanumeric presented tachistoscopically.

Method

Fonts. Three 5 × 7 fonts, shown in Figure 79, were compared for legibility. The first ("maximum dot") font was constructed utilizing as many dots as possible in a 5 × 7 field; thus, it gives a boxy, squared-off appearance. The second ("maximum angle") font was constructed using the fewest dots possible in a 5 × 7 field. This font has a rather angular appearance. The third font is the Lincoln/Mitre font as used in the VanderKolk, *et al.* (1974) study.

Apparatus. The display device used in this experiment was the same Tektronix 4014-1 computer terminal used in previous studies. The display was generated by the PDP 11/10 minicomputer, which also controlled the flow of the experiment by logging subjects in, presenting the display, and recording responses. The Tektronix display was placed in an experimental room equipped with a forehead rest to maintain the viewing distance at 62 cm.

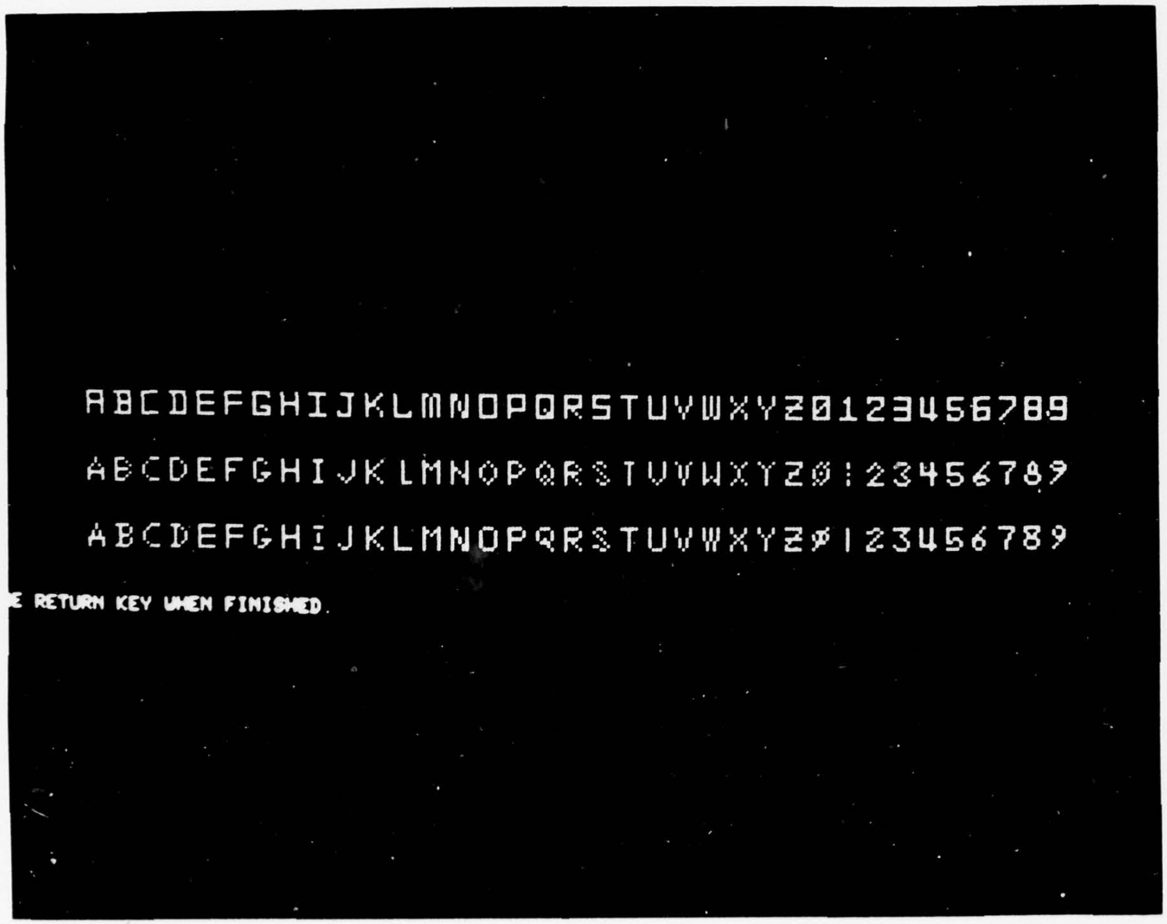

Figure 79. Maximum Dot (top), Maximum Angle (center), and Lincoln/Mitre Fonts

Subjects. Twenty subjects, 14 male and 6 female, were obtained from the student population of the University. Subjects were not paid, but participated voluntarily. There was a cash reward offered for the subject having the most correct responses. All subjects were given a full vision test with a Bausch and Lomb Orthorater and were required to have 20/20 vision (near and far, correct or uncorrected).

Procedure. Each subject was seated comfortably in the experimental room, following which the forehead rest was adjusted for the subject's seated height. The experimental program was initiated and the subject was instructed to type his or her name on the terminal keyboard. The experimenter then left the room. The first phase of the experiment consisted of familiarization with the alphanumerics to be used. All 36 characters from each font were displayed simultaneously on the CRT. The subject was then asked to study the display until he or she felt reasonably certain that each character could be identified correctly. This side-by-side presentation allowed the subject to note any differences and similarities among certain characters in the fonts. Although no time limit was placed upon this familiarization, no subject took longer than 5 min.

After the subject was reasonably familiar with the characters, the next phase of the experiment was begun. This second phase consisted of six typing trials. Each trial consisted of a fixation box (approximately 1.1 by 1.6 cm) being displayed on the center of the display with a randomly selected alphanumeric inside the box. The subject's task was simply to type in the displayed alphanumeric. The purpose of these typing trials was to familiarize the subject with the location of the fixation box and the alphanumerics as well as with the keyboard. As soon as the subject responded, the screen was erased and the next trial was begun. These responses were not recorded.

The experimental phase began immediately after the typing trials ended. Each experimental trial consisted of the following sequence of events:

1. The fixation box was displayed centrally on the CRT.

2. Approximately three seconds later a randomly selected alphanumeric was displayed within the fixation box. The font for this alphanumeric was also randomly selected.

3. Forty milliseconds after it was written, the alphanumeric was overwritten with a full 5 × 7 matrix of dots.

4. The subject then typed in the alphanumeric he or she had seen; if uncertain, the subject was forced to make a (guessed) response.

5. The screen was erased and the sequence repeated.

The random number generator was constrained so that the same alphanumeric could not be presented on two consecutive trials. A block of trials consisted of each alphanumeric from each font presented once, or 108 trials per block. The subjects were given a rest period, if they desired, after two blocks were presented and again after four blocks. The entire experiment consisted of six trial blocks, or 648 trials.

Results

The results were analyzed parametrically in terms of total errors and by conventional confusion matrices. These analyses were performed on data from the last four trial blocks. The total errors per font over the last four blocks are summarized in Table 35, which shows that font had a highly significant ($p < .001$) effect on the total number of errors. A Newman-Keuls comparison of the three fonts confirmed that fewer errors were obtained with the maximum dot font than with either the Lincoln/Mitre font (658 *vs*. 789, $p < .01$) or the maximum angle font (658 *vs*. 764, $p < .01$). The maximum angle font produced approximately the same number of errors as the Lincoln/Mitre font ($p > .05$).

TABLE 35. Analysis of Variance of Errors for Three Fonts and Four Trial Blocks

Source of Variance	*df*	*MS*	*F*
Fonts (F)	2	60.463	11.28[a]
Subjects (S)	19	328.223	
F × S	38	5.362	
Trial Blocks (B)	3	25.549	4.79[b]
B × S	57	5.332	
F × B	6	1.657	0.58
F × B × S	114	2.866	

[a] $p < .00015$. [b] $p < .005$.

A reliable learning effect was also revealed by the analysis of variance ($p < .01$). A Newman-Keuls analysis of trial blocks revealed that fewer errors were obtained on the last experimental trial block than with either the third experimental block (500 *vs*. 581, $p < .05$) or with the fourth experimental block (500 *vs*. 584, $p < .05$). This decrease in errors can be seen in Figure 80. The relative differences among fonts remain unchanged even though the subjects' performance was not completely asymptotic through the four experimental trial blocks, as indicated by the nonsignificant Font × Trial Blocks interaction.

The confusion matrices obtained for the three fonts are shown in Figures 81, 82, and 83. The most severe confusions occur for different alphanumerics with each of the font styles. In the maximum dot font, the characters M, Q, S, U, V, 0, 1, 2, 7, and 8 were confused with other characters more than 25% of the time. In the minimum dot font, the subjects confused I, J, O, Q, S, U, V, Z, 0, 1, 3, 6, and 9 with other alphanumerics more than 25% of the time. In the Lincoln/Mitre font, the characters A, I, J, O, Q, S, U, V, W, Z, 0, 1, 2, 3, 5, and 8 were confused more than 25% of the time.

Discussion

The superiority of the maximum dot font in this study can be partially explained by the greater percent active area (VanderKolk, *et al.*, 1974) of this font in relation to the two other fonts. For most characters, there are simply more dots used in this font. This greater number of dots results in a distinct subjective brightness increase over the other fonts, even though the dot luminance, measured microphotometrically, was the same for all fonts.

In addition to a subjective brightness difference, the method of presentation may favor one font over others. The tachistoscopic presentation method was chosen for purposes of comparison with other studies in which this method was used. The most obvious shortcoming of

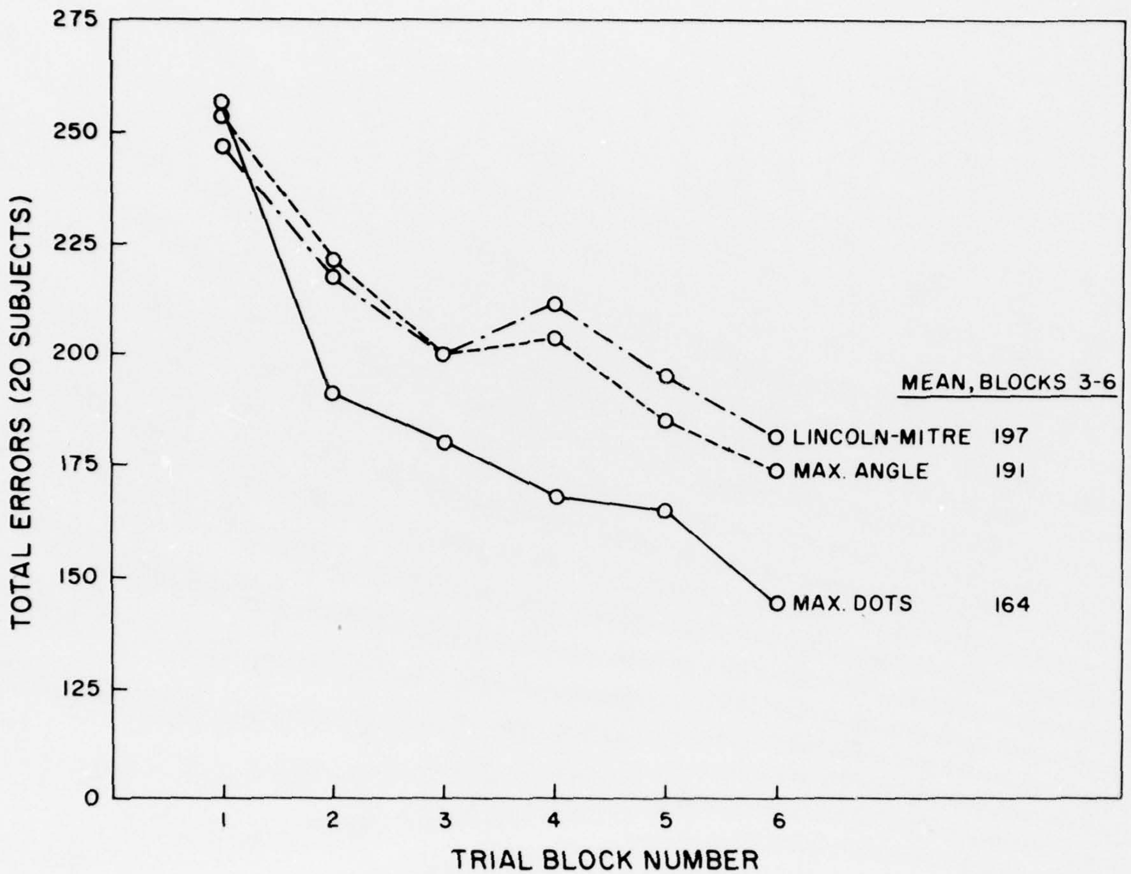

Figure 80. Number of Errors for Each Font

R\S	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A				1									1	1		1			1				1								1		2		5		14
B								1				1																		5					20		27
C									1							2												1			1						5
D										1					2																				1		4
E			5																							1	1			1		1			1		10
F					1		1																														2
G				1	1	2		1									9	1	1													1	8		3		28
H	7			1									1	1	1	1														1			1		1		15
I				2									1							1			1					12									17
J												1					1				1							1									4
K			2			1		1					1	1	1						1			2		1									1		12
L		1															1											2									4
M				1								1		1																	1						4
N	1				1			2	1	1		1	8		1	1		1					1					1			1						21
O				5						1		1				1	2																				10
P	1	1				1				1				1	1							1								1					1	1	10
Q			1	1											2												1										5
R	4	3		2				1						1		4				1			1				1	1				1			4	1	25
S															1													1				2				3	7
T				1					5	2			5															1									14
U									1		1	1	1								1	1								2							8
V								1									1				3		1		7						2					1	16
W									1			2		1			8				22	3			1		1	1			11						51
X				2					1					1			1				1	4			6	1	1	2		1							21
Y										1			4				1				1	39															46
Z		2																									36		22					21	1		82
0				1						2					3																				1		7
1													1								1																2
2																	1									13	13							6			33
3																	1									1											2
4												1	1							1							1	1									5
5										1		1							64																	5	71
6	2	1	1			2	1		1						1	1	1		5								2					9			2	1	30
7				1									1		1		1			1					1		8		3								17
8	1	3		1						1							2	1						1			3									1	14
9																			1		1									1		1			1		5
bl	1				1										1						1	1	2								1			1	1		10
Σ	17	11	9	20	4	6	2	7	11	11	1	10	25	8	15	11	30	3	72	4	33	49	7	3	15	17	68	24	25	12	18	15	11	28	43	13	658

FONT: MAXIMUM DOT

Figure 81. Confusion Matrix for Maximum Dot Font. S indicates stimulus presented, and R indicates response. Errors in excess of 25% are highlighted.

R\S	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A															1		4					1					1	2			1						10
B						1	1											1	1									1		4					3		12
C					1										2		1											1									5
D															2												2										4
E		1				1																		1		2		1							1	1	8
F					1							1								1						1											4
G						1											3															1	1				6
H						1																						3			4	1			1		10
I																				4			1					5									10
J									2			3					1			1				1			1										9
K	2		17	1								3	2	1	2	1	3	1	7			1	1	1			8	8		12			7			1	79
L						1										1											1										3
M															1		1			3	1						1										7
N	1							2	1	2		3	2						3	3							2	5									24
O						1										1	5										5										12
P																								1				1				2		1	1	1	7
Q				1		1									4	1				1							4										12
R				1	1	2		2	1		1				2	2	3		3									3		1	1						23
S									1							2											1				1		1				6
T							1		12													8						8						1			30
U									2	13												5						2			1						23
V				1						41		1			1				1	1	55		1		2	1	6	4								2	117
W	1	1			1					1		4					8				7	13					3			1	1				1		42
X	4								2					4			1		10		2	1			1	1	11	10	1	4					1	1	54
Y								1	1	4			1		1		2		1		5	10					4	10			1						41
Z									2						1				1								2	3	7				8			3	27
0															8		4							1				1								1	15
1																				1																	1
2	3								1							2	3		1			1				14	1	1		1			1	1		4	34
3																			1								1	1	2				2			1	8
4																												2		1			3				6
5									1																											1	2
6	1		1			1				1							2		2					1			3	1		4		3			12		32
7							1								1	2										1		3					1			29	38
8		1			1		1					1		1	2	1	4		5	1				1		1	1			2		1	1				25
9									2	1					1												1		2					1			8
bl		1						1														1	1	2		1				1		1			1		10
Σ	12	4	18	4	5	10	4	6	28	63	1	16	5	6	29	13	45	2	36	16	70	41	4	9	3	22	59	76	12	31	10	9	25	4	21	45	764

FONT: MAXIMUM ANGLE

Figure 82. Confusion Matrix for Maximum Angle Font. S indicates stimulus presented, and R indicates response. Errors in excess of 25% are highlighted.

R\S	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A						1																	1	1		1	1										5
B			1						1																										5		7
C				1								1					1																				3
D															15												1										16
E						2			3				1							1						1		1				1					10
F					3				1		1															1	1										7
G			1		4	1			2																												8
H			1											1			1			1			1					2				1					8
I																				2								16									18
J									1					1						2								2			1		1				8
K			15					3		1						1	1		3								2			6			11				43
L				1													1											1									3
M	5					1				1	1										3	1	3					3			2		1			1	22
N	1							1		2			2						4		2		2					19									33
O									2								1				1																4
P						1					1						1										6							1	1	2	13
Q				1			1								2												3										7
R		3		1		1								1		9	35			2										1					2	1	56
S																											1		1			1			1	2	6
T									11																		1	11									23
U										15					1							2		1			1				2					1	23
V									2	1											4		6		1			5									19
W	2			1				1	2	11		1		1			2		1		13	15			1			2			9					1	63
X	11							1	3				2	2			3		6			5	4		10		15	2	2						18	1	85
Y	1							1	5				2		1		1			2		20	9				2	7							1	1	53
Z	1							1	8						1				1	1				2			5		39	1				5			65
0	2					1			1						3				1									1							2		11
1									3																				1								4
2	1										1		1													17	2	1		1	1			1			26
3		1							1										3																4		9
4									1													1			1												3
5	1	1																1	5	1										2						1	12
6	3				1	2			2			1	1						3							2	1	1		7		19			8		51
7				1										2	1											1	13	1	1			1	1		1	3	26
8									1						2	1			6			1					1		1	2		1				2	18
9		1			1				2								1										3				1						9
bl	1						1				1				1								1	1	1					1		1	1			2	12
Σ	29	6	18	6	9	10	2	8	52	31	5	3	9	8	27	11	48	1	33	12	23	45	27	5	14	23	59	75	45	21	16	25	15	7	43	18	789

FONT: LINCOLN / MITRE

Figure 83. Confusion Matrix for Lincoln/Mitre Font. S indicates stimulus presented, and R indicates response. Errors in excess of 25% are highlighted.

this presentation method is the absence of any contextual advantage (or disadvantage) of a particular font.

Conclusions

The results of this study indicate that fonts which have been optimized for stroke characters are not necessarily the most legible when used in a computer-generated dot-matrix display. Indeed, these results suggest that an optimum font should contain characters from several existing fonts. The results suggest that this type of experiment should be replicated and extended to other matrix sizes, and to combined upper- and lower-case displays; the practical results of such studies should become apparent to and adopted by display manufacturers. Further research of this nature is presented in the next section.

VIII. FONT OPTIMIZATION FOR 5 × 7, 7 × 9, AND 9 × 11 DOT-MATRIX ALPHANUMERICS

Introduction

The previous section described the first study conducted to compare three candidate dot-matrix fonts for single character legibility. From those data, a preliminary optimum font, a composite font with minimal confusion frequency, was selected for subsequent experiments. This minimal confusion font was used in the experiments reported in Sections III and IV of this report.

Subsequent to the completion of several experiments reported previously, it became apparent that more information was required about font legibility for (1) an additional font, the Huddleston font, and (2) other matrix sizes. Thus, the experiment described in this section of the report fills those needs. In addition, it replicated the previous font study to reexamine the results for a possible equipment flaw which was thought to have biased the results.

In this experiment, three matrix sizes (5 × 7, 7 × 9, 9 × 11) were evaluated for four different fonts (Lincoln/Mitre, Maximum Angle, Maximum Dot, Huddleston) in a forced-choice, single alphanumeric tachistoscopic recognition experiment. The procedures were similar to those reported in Section VII.

Method

Subjects. A total of 40 subjects, 20 male and 20 female, were used in this study. All subjects were screened for normal acuity, at least 20/25 corrected, and absence of gross visual defects using a Bausch and Lomb Orthorater. Each subject served a total of approximately four hours and was paid for his/her participation.

Apparatus. The display used in this study was the same Tektronix 4014-1 terminal used in earlier research. In order to increase the data transmission capabilities of the display, a major modification to the character generation circuitry was made. Two special programmable read-only memories (PROMs) were implementd as the alternate character set feature of the 4014-1. By programming the PROMs and selecting the alternate character set from software, individual dots in dot-matrix characters were designed to be any shape and size, and then written using only a single character write command. This proved to be much faster than the earlier method of drawing each dot of the dot-matrix character by illuminating a certain sequence of pixels on the face of the Tektronix. The older method required much more complicated software and necessitated sending up to 100 bytes per dot for each dot in a character. The new method required only 6 bytes per dot.

The computer system used in this study was a PDP 11/55 machine, which is similar to the PDP 11/10 used in previous studies, but it is much faster and contains more mainframe memory. The computer was linked with the LPS-11 time base in order to accomplish all timing delays for generating the dot-matrix characters. In addition, an ASCII keyboard was connected to the computer system through the intra-lab connection system. This keyboard served as the subjects' response apparatus such that all data were entered into the computer via the keyboard.

The only other major piece of equipment was a combination forehead rest and keyboard table which was located within a curtained cubicle inside the experimentation room. The Tektronix display was also located within this cubicle. The forehead rest was used to keep the plane of the subjects' eyes approximately 102 cm from the surface of the display.

Experimental design. The basic experimental design for this study is shown in Figure 84. Four character fonts were used in the study. Two of these fonts (Lincoln/Mitre and Huddleston) were designed for specific applications and have been reported in the literature. The remaining two fonts were designed in our laboratory and were described in the previous section. Figures 85 through 104 illustrate the several fonts.

The five character size/matrix size combinations included the standard matrix sizes (5×7, 7×9, and 9×11), allowing the character size to expand as more dots are added to the matrix. The 5×7, 7×9, and 9×11 matrices were 14.4, 18.7, and 22.9 mm high, respectively. At the 102 cm viewing distance, they subtended vertical angles of 48.5, 63.0, and 77.2 arcminutes. The remaining two levels were obtained by designing a 7×9 and 9×11 matrix size character set which remained the same size as the 5×7 characters. This was done by retaining the same dot/space ratios but reducing the absolute size of the dots and spaces. These additional levels allowed the effect of character subtense to be separated from the effect of matrix size (number of dots).

A learning effect has been found to exist in this type of study, i.e., tachistoscopic presentation of single alphanumerics. To make certain that a plateau was reached before experimental trials were begun, each subject was given a series of practice trials on his/her

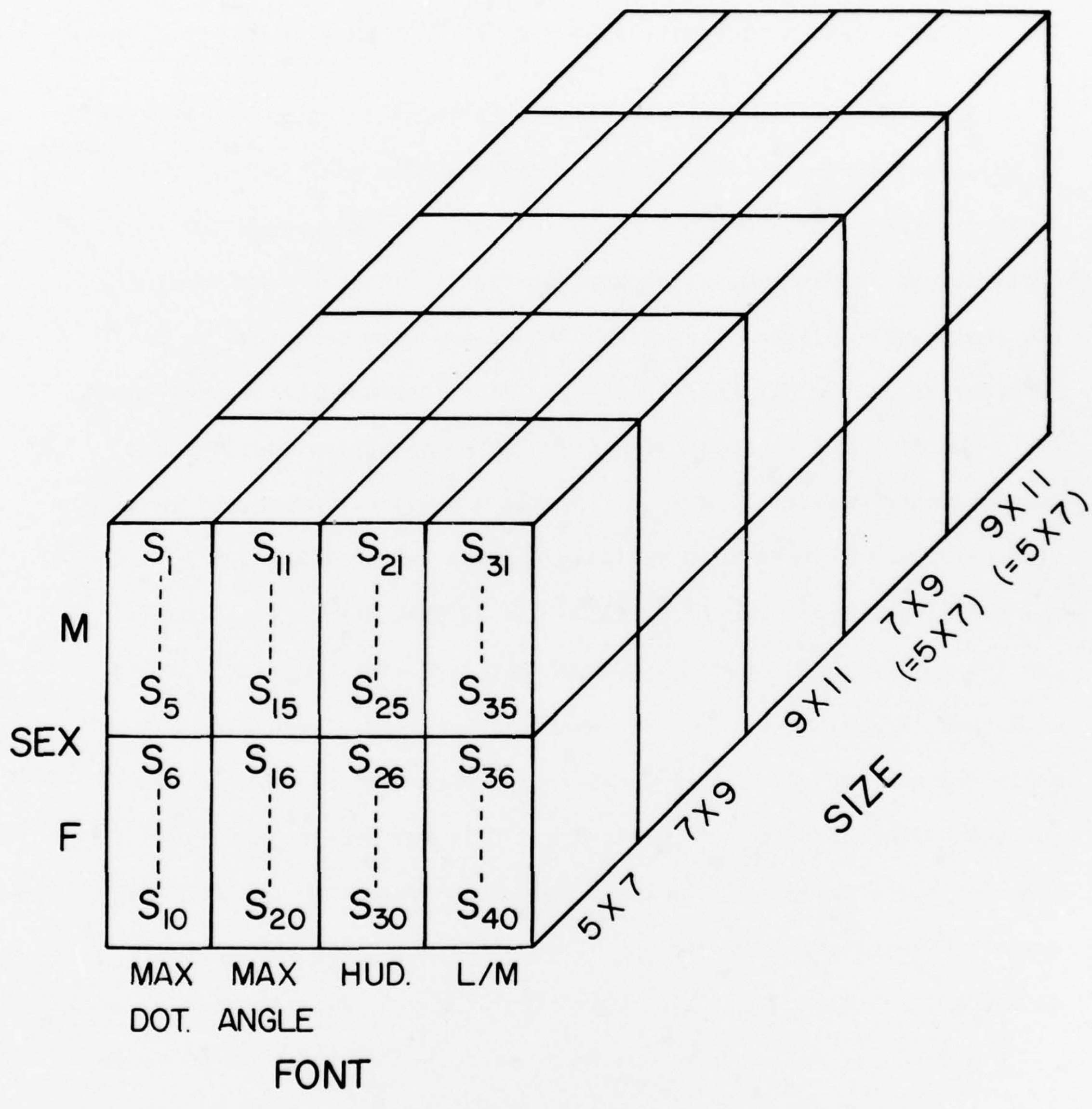

Figure 84. Experimental Design, Second Font Study

Figure 85. Huddleston Font in 5 × 7 Matrix

Figure 86. Huddleston Font in 7 × 9 Matrix

Figure 87. Huddleston Font in 9 × 11 Matrix

Figure 88. Huddleston Font in 7 × 9(= 5 × 7 Size) Matrix

Figure 89. Huddleston Font in 9 × 11(= 5 × 7 Size) Matrix

Figure 90. Maximum Dot Font in 5 × 7 Matrix

Figure 91. Maximum Dot Font in 7 × 9 Matrix

Figure 92. Maximum Dot Font in 9 × 11 Matrix

Figure 93. Maximum Dot Font in 7 × 9(= 5 × 7 Size) Matrix

Figure 94. Maximum Dot Font in 9 × 11(= 5 × 7 Size) Matrix

Figure 95. Maximum Angle Font in 5 × 7 Matrix

Figure 96. Maximum Angle Font in 7 × 9 Matrix

Figure 97. Maximum Angle Font in 9 × 11 Matrix

Figure 98. Maximum Angle Font in 7 × 9(= 5 × 7 Size) Matrix

Figure 99. Maximum Angle Font in 9 × 11(= 5 × 7 Size) Matrix

Figure 100. Lincoln/Mitre Font in 5 × 7 Matrix

Figure 101. Lincoln/Mitre Font in 7 × 9 Matrix

Figure 102. Lincoln/Mitre Font in 9 × 11 Matrix

Figure 103. Lincoln/Mitre Font in 7 × 9(= 5 × 7 Size) Matrix

Figure 104. Lincoln/Mitre Font in 9 × 11(= 5 × 7 Size) Matrix

first day of participation. Since each subject saw only one font, the size for practice was completely counterbalanced across subjects within each font/sex cell.

To minimize any systematic ordering effect, the order of size presentations was randomized. Once the orderings were obtained, one male and one female subject were run under each ordering. The runs were split into two days to minimize fatigue, and the orderings were constrained so that the first size seen on the second day was the same as the practice size seen on the first day. All of these precautions served to make any significant ordering, learning, or fatigue effects highly improbable.

Procedure. Subjects were seated comfortably behind the forehead rest in front of the Tektronix display. The subject was then informed that the entire set of alphanumerics which would be seen on the experimental trials would be displayed simultaneously until the subject was familiar with them. It was emphasized that any similarities or differences among the characters should be noted.

The experimenter then explained the presentation and response entry procedure and answered any questions posed by the subject. The subject was also told of the intercom link between the computer room and the experimental room. For the first day of trials, the subject was told that the first few trials were practice trials. After this, the experimenter retired to the computer room, initiated the program, and asked the subject, via the intercom, if he/she was prepared to begin.

The program for day one included a brief review of instructions, a series of graphic instruction pages reviewing the method of presentation and response. The actual study contained one practice and two experimental sizes on day one and three experimental sizes on day two. Thus, three sizes were shown on each day. The procedure for each size was nearly identical, as follows.

For each size, the entire set of characters was displayed on the CRT. This included the letters A through Z and the numerals 0 through 9. The subject had as long as he/she desired to look over this character set. In practice, no subject took longer than three or four minutes for this phase. After the familiarization phase, a short review of instructions was given if the subject was on day one of the trials.

The experimental trials always consisted of the same sequence of events. First, a fixation box was drawn in the middle of the screen. A short time later a single character was placed in the middle of the box. Each character was constrained so that the average time to write an entire character of any size from any font was 35 ms (±0.5 ms). After the character was fully written, the program delayed 10 ms and overlaid the character with a full matrix of dots.

After the character was erased, a prompting message appeared in the lower left-hand corner of the display. Following this message, the subject typed in the character which he/she saw, or thought he/she saw, on the preceding trial. When this response was entered, the screen was erased and the next trial was begun.

The experimental trials were blocked. Each block contained two presentations of every character in the set, or 72 total trials per block. An experimenter-controlled rest break was initiated after every two blocks or 144 trials. A total of 4 blocks (288 trials) was given for each experimental size. The practice size was given for a total of 6 blocks (432 trials) to assure that the subjects reached a performance plateau.

Day one and day two procedures were essentially the same. On day two, no extensive instruction period was required and all sizes were run for four blocks of trials.

Data. All character presentations and subject responses were stored on disk. An analysis program compared responses with presentations, tagged errors, tabulated statistics, and formatted the output for each subject. From these data sheets, confusion matrices were constructed and statistical analyses were run.

Results

Number of errors. The mean numbers of identification errors per subject per experimental condition were evaluated by an analysis of variance, which is summarized in Table 36. Individual comparisons were made by the Newman-Keuls technique for all meaningful significant effects. From Table 35, it can be seen that the Font and Character/Matrix Size main effects and their interaction were all statistically significant ($p < .05$).

The Font main effect is illustrated in Figure 105, which indicates that there is no overall significant difference between the Huddleston and Lincoln/Mitre fonts ($p > .05$), and that each of these was superior to both the Maximum Angle and Maximum Dot fonts ($p < .01$). Further, the Maximum Dot font was found to be superior to the Maximum Angle font ($p < .05$).

TABLE 36. Summary of Analysis of Variance for Correct Responses

Source	*df*	*MS*	*F*	*p*
Font (*F*)	3	5473.58	2.97	0.046
Character/Matrix Size (*C*)	4	3087.61	21.50	0.0001
Sex (*S*)	1	1866.60	1.01	0.32
$F \times C$	12	308.26	2.15	0.018
$F \times S$	3	577.10	0.31	0.82
$C \times S$	4	116.37	0.81	0.52
$F \times C \times S$	12	43.98	0.31	0.99
Subjects within Font, Sex (*Ss/F,S*)	32	1843.06		
$C \times Ss/F,S$	128	143.60		
Total	199			

The Character/Matrix Size main effect is illustrated in Figure 106, which shows several interesting results. First, the 5 × 7 matrix size produced more errors than any of the other sizes ($p < .01$). The 7 × 9 matrix size yielded the next largest error total, and was in turn inferior to all three remaining matrix/character sizes ($p < .01$).

The next poorest size was the 7 × 9 matrix size reduced in character size to be equal to the 5 × 7; it, in turn, was inferior to both the 9 × 11 and the reduced 9 × 11 size. The next poorest was the 9 × 11 size, which was inferior to the reduced 9 × 11 ($p < .01$). In summary, the larger the matrix size *and* the smaller the character size, within the bounds of the present experiment, the fewer the recognition errors.

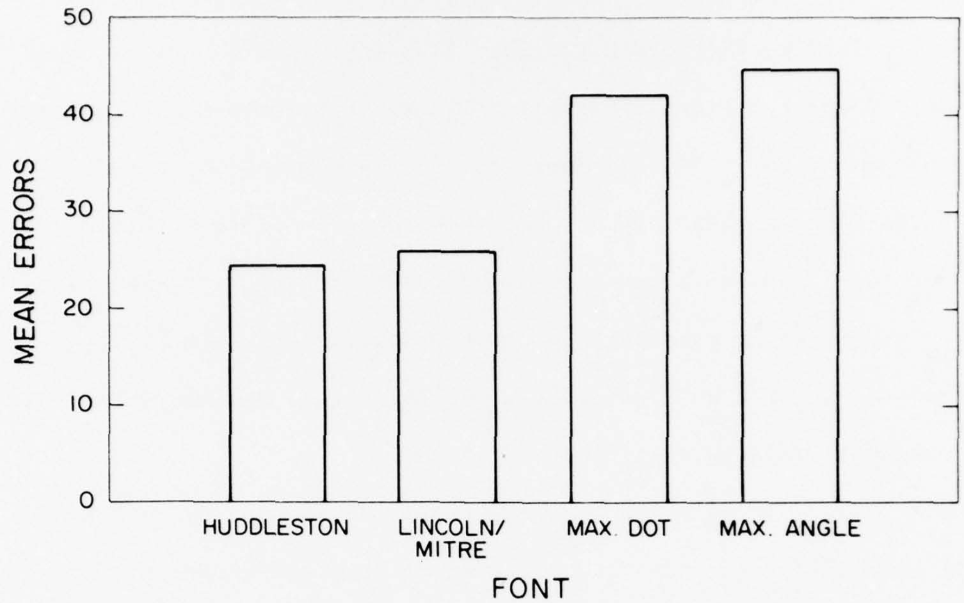

Figure 105. Effect of Font upon Number of Errors

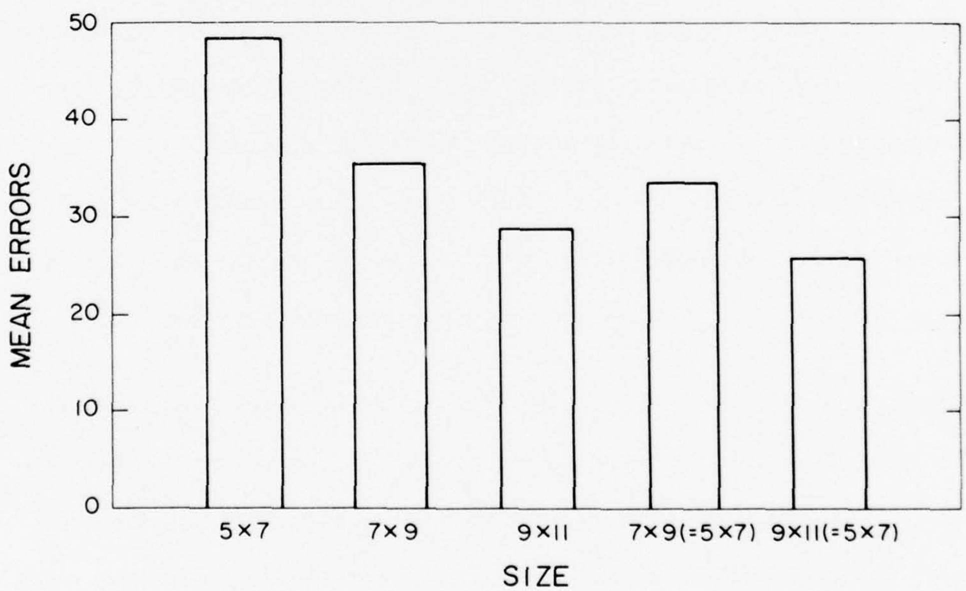

Figure 106. Effect of Character/Matrix Size upon Number of Errors

The Font × Character/Matrix Size interaction is shown in Figure 107. For the 5 × 7 size, the Huddleston font is superior to the other three ($p < .01$), while the Lincoln/Mitre and Maximum Dot fonts are essentially equivalent ($p > .05$). In this matrix size, the Maximum Angle font produced more errors than any of the other three fonts ($p < .01$).

For the 7 × 9 font, the Lincoln/Mitre was superior to the other three ($p < .05$ for Huddleston; $p < .01$ for other comparisons). All comparisons among the Huddleston, Maximum Angle, and Maximum Dot error rates are statistically significant ($p < .01$).

Similarly, all comparisons among fonts for the 9 × 11 matrix size are statistically significant (Huddleston *vs.* Lincoln/Mitre, $p < .05$; Maximum Angle *vs.* Maximum Dot, $p < .05$; all remaining comparisons, $p < .01$). For this matrix size, the Lincoln/Mitre is best and the Huddleston next best.

The Lincoln/Mitre and Huddleston fonts are essentially equivalent ($p > .05$) for the reduced 7 × 9 size, while all other comparisons are significant ($p < .01$), with the Maximum Angle the poorest.

Similarly, for the reduced 9 × 11 size, the Lincoln/Mitre and Huddleston fonts are nondifferent ($p > .05$), with the Maximum Angle font again the poorest ($p < .01$) and the Maximum Dot font next poor ($p < .01$).

Confusion matrices. As in the previous font study, much can be learned from the confusion matrices, which are illustrated in Figures 108-127. For example, in the Maximum Dot font, major confusions were between 5 and S, 2 and 7, Y and V. The Y-V confusion also existed with considerable frequency for the Huddleston and Lincoln/Mitre fonts, while 4-1 confusions were also frequent for the Huddleston and Z-2 for the

Lincoln/Mitre. Of interest is the fact that there were no predominant confusions for the Maximum Angle font; rather, the errors were distributed throughout the confusion matrices. The implication of this result is not totally clear.

It seems unnecessary to speculate further on "best" font combinations. While selected alphanumerics could be extracted from all four (and other) fonts, the resulting combination would require subsequent experimental evaluation. At this point, it seems clear that the choice of Huddleston or Lincoln/Mitre, based upon the matrix size, remains well advised.

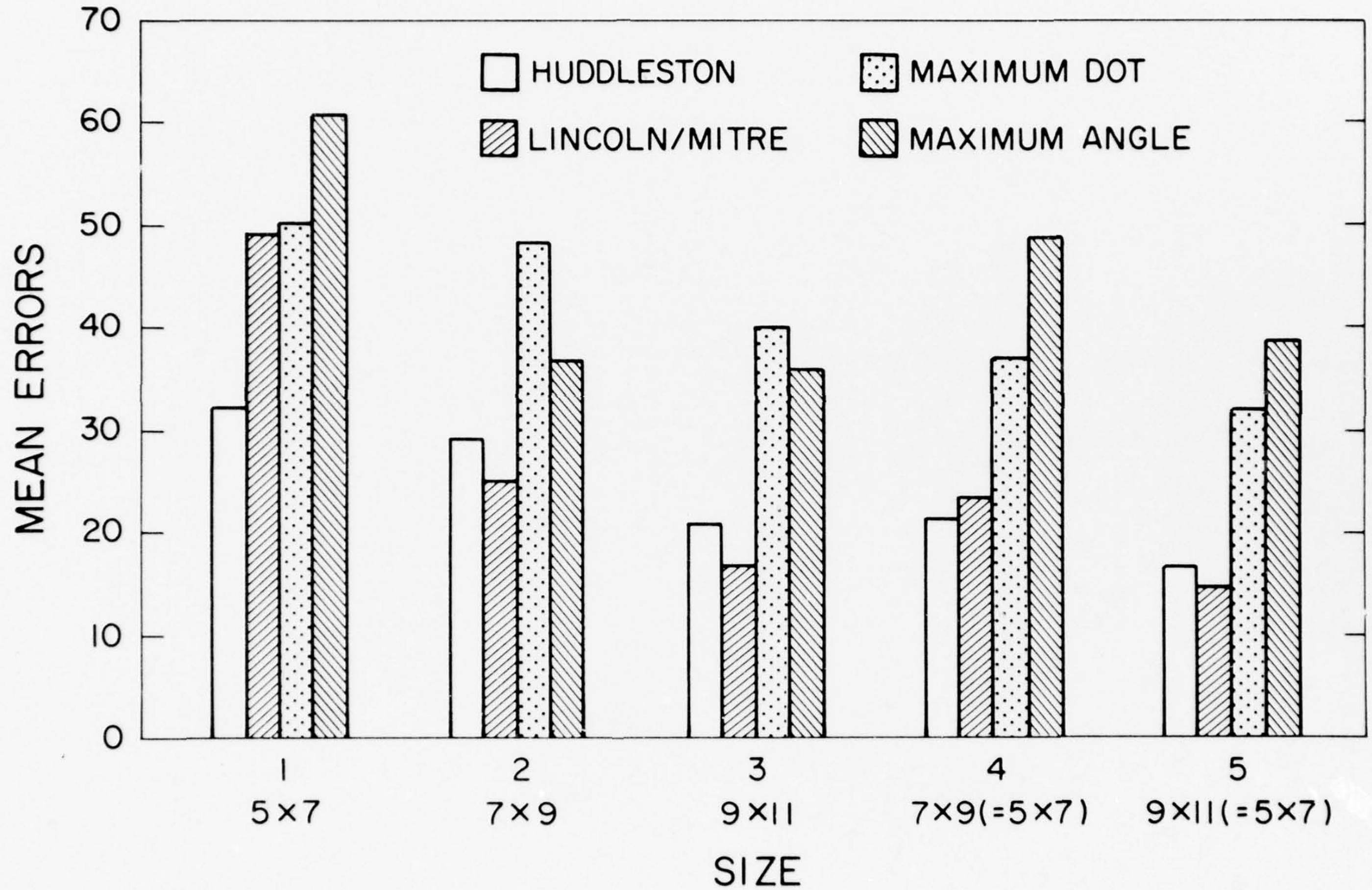

Figure 107. Effect of Character/Matrix Size by Font Interaction upon Number of Errors

S\R	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A		1								1												1	5	1		1											10
B				2	1												1			3						3								1			11
C							1				1																							1			3
D						1																															1
E						4												1															1				6
F																2																					2
G			2														1																				3
H						1							1																		2						4
I				4	1					2				1					1	13					1	3		5	1		1		1	4			38
J														1							1									1							3
K																																					0
L					1						1														1			1		1	1						6
M								1						3																							4
N								1		2			3									2		4	2						1						15
O				1													3										2										6
P						1												9																			10
Q																		13		1							4		4		1			1	1	5	30
R																1																					1
S									1								1							1	1	2	2	1	2	4	2	2	2		2		23
T																									2						1			1			4
U																						1															1
V																					1		10	1	27												39
W													1				1					8		1	25	1			1			1		2			41
X			1								3		1									1			1												7
Y																						4		1											1		6
Z																													13	1				4			18
0																4								1		6			3			1		9		6	30
1									12	2	1					2		1	3	12		1		3	5				1		2	1	1	2	1		50
2																										19	2	1		1			1	3		2	29
3								1		5																			1								7
4		1								1											2		1							1							6
5																			1														5				6
6																																1		1	1		3
7																		1								6											7
8		3					1			1									1					3	2	3				24		4	2	1			45
9				1							1										1				1	2	2		4					2			14
Σ	0	5	3	8	3	7	2	3	13	14	7	0	6	5	0	9	7	25	6	29	5	18	16	16	68	46	12	8	30	33	11	10	13	32	6	13	489

FONT: LINCOLN / MITRE 5x7

Figure 108. Confusion Matrix for 5 × 7 Lincoln/Mitre Font

S\R	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A																								2										1			3
B																																					0
C						1	6															1															8
D					1																																1
E																																					0
F					2		1																														3
G						1		1							2		3																				7
H																																					0
I				1	1			1												3					2			1		1		1	2	1			14
J			1																1		1				1						1	2		1			8
K		1																																			1
L					2									1											1				1			1		1			7
M						1								1																							2
N		1											1																								2
O																											3										3
P		1																3																			4
Q															1			6											1								8
R					1															1																	2
S																																					0
T																			1						4		1										6
U				1																		1		1													3
V																		1			1		3	2	18	1		1						2			29
W																			1												1						2
X																									1												1
Y		1		1																						1											3
Z																													5					1			6
0																1	1									1						1	3	11		2	20
1	1					1	1	3	6	2		1						1	4	4	1	2			7	1	1		1	1	5		3	3		1	50
2											2					1		1								29		1						3		2	39
3																																					0
4		1																			1											1					3
5																		1	1														1		1		4
6																				1																	1
7																									2	7			1						1		11
8																																	1	2		1	4
9																1													1								2
Σ	1	5	1	3	7	4	8	5	6	2	2	1	1	2	3	3	4	13	8	9	4	4	3	5	36	40	5	3	10	2	7	6	10	26	2	6	257

FONT: LINCOLN/MITRE 7x9

Figure 109. Confusion Matrix for 7 × 9 Lincoln/Mitre Font

S\R	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A																																					0
B																																					0
C																						1															1
D																																					0
E						2	1											1																			4
F																		1																			1
G						1																															1
H																		1																			1
I		2			1															4					3	1		2									13
J																			1		6			1	1				1	1			1				12
K										1																											1
L																																					0
M																																					0
N																																					0
O																	4										1										5
P															1			5																			6
Q																1							1				1									1	4
R					1																																1
S																										1									2		3
T								1																	2												3
U																						1															1
V																				1			2	1	4	1											9
W																									6												6
X																																					0
Y																																					0
Z	1																							1										2			4
0		2		1	1		1			2	1					2			2				1		3	4			4		4	1	3	3	1		36
1				1	1				7							1				10			1		6	2					5			1	1		36
2																										5										1	6
3																															1						1
4																																					0
5																																					0
6																							1								1			4			6
7																										7											7
8																														1				1			2
9																								1													1
Σ	1	4	0	2	4	3	2	1	7	3	1	0	0	0	1	4	4	8	3	15	6	2	6	4	25	21	2	2	5	2	11	1	4	11	4	2	171

FONT: LINCOLN/MITRE 9x11

Figure 110. Confusion Matrix for 9 × 11 Lincoln/Mitre Font

S\R	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A																																					0
B																																					0
C							4																														4
D																		1																			1
E			1				1																														2
F	1				1							1																									3
G				1																																	1
H													1																								1
I				1																7	1			1	1	1								1			13
J								1											1		3			1						1							7
K																																					0
L						1				1								1											1								4
M																																					0
N																													1								1
O																	3										1										4
P		1				2									1			10																			14
Q																		6												1					2		9
R																																					0
S											1													1										1			3
T									1									1				1			3			2				1			1		10
U																									1												1
V							1														1		2	5	12				1								22
W					1																			1							1						3
X			1																						1												2
Y											1													2													3
Z																													3					1			4
0																1			1						1			2					3	2	1	1	12
1						1		1	2	10	1						1	1	3	5				1	5	4	1			1	10			2			49
2		1																								37								4			42
3										1																											1
4																																					0
5																		1																1			2
6																																		1			1
7																				2					2	1			2							1	8
8																								1										2			3
9																											1								1		2
Σ	1	2	2	2	2	4	6	2	3	12	3	1	1	0	1	1	4	21	5	14	5	1	2	13	26	43	3	4	8	3	11	1	3	15	5	2	232

FONT: LINCOLN/MITRE 7x9 (=5x7)

Figure 111. Confusion Matrix for 7 × 9(= 5 × 7) Lincoln/Mitre Font

S\R	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A																										1											1
B																						1											1				2
C																																					0
D			1																																		1
E						1												2																			3
F							1																														1
G						1																															1
H																																					0
I							1											1		5					1			2						1			11
J							1	1													3					1					1						7
K																																					0
L																																					0
M																																					0
N																																					0
O																											5										5
P						1												4																			5
Q															1	1																					2
R																																					0
S											1													2						1					2		6
T									1																4												5
U																																					0
V	1																				1		2		1												5
W	1																					3			2									1			7
X																																					0
Y														1																							1
Z																								1				1									2
0		1		1					2		1			1		1	2			2					2				2		2		1	2	2	2	24
1		1		1	1				5		1	1		1					2	14		1	2	1	3	1	1		2		4		1				43
2																										5											5
3																																					0
4																					1																1
5																																					0
6		1																								1								2			4
7																									1	3			3								7
8		2																							1								1	1			5
9																																			1		1
Σ	2	5	1	2	1	3	3	1	8	0	3	1	0	3	1	2	2	7	2	21	5	5	4	4	15	12	6	3	7	1	7	0	4	7	5	2	155

FONT: LINCOLN / MITRE 9 x 11 (=5x7)

Figure 112. Confusion Matrix for 9 × 11(= 5 × 7) Lincoln/Mitre Font

S\R	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A																															1						1
B														1							1							1					1				4
C							3								1												1										5
D																																					0
E						1										1		1															1				4
F		1			3											1		1																1			7
G						1																											1				2
H	1																						1	2	2												6
I		1		1	1	1	1			1										8											1	1					16
J												1									8																9
K																								1													1
L			1		1																	1							1				2				6
M								11						1									2	3		1		2									20
N								9			2												7	3							1						22
O				2													1										5		2								10
P						5							1					2																	1		9
Q															1			3											2								6
R																2																1		1			4
S			1																					1		3	3		1	1		2	4		1		17
T				2		1			1				1					1								1			1				1	1			10
U																						6															6
V		1																			2		2		33			1									39
W																					1						1	1									3
X																																		1			1
Y																								2									1	1			4
Z																													7		1			6			14
0		2					2	1							5		3	1			2								5				1	2			24
1				1	2	1			4	1	1	2		1		1			1	5	1	1	1	1	3	1	1		4		8		1	1			43
2																										1											1
3					1													2						1					1		1	3		2			11
4																													3								3
5																			1															1			2
6																																					0
7																1									1	2				1					1		6
8																																					0
9																													1								1
Σ	1	5	2	6	8	10	6	21	5	2	3	3	2	3	7	6	4	11	2	13	15	8	13	14	39	9	11	5	27	2	13	7	13	17	3	0	317

FONT : HUDDLESTON 5 x 7

Figure 113. Confusion Matrix for 5 × 7 Huddleston Font

S\R	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A																		1																			0
B																																				1	1
C							2																						1								3
D						1																					1					1					3
E																					1							1				2					4
F	1				5			1			1					3		2	1	1														1			16
G						1																											5				6
H		1								1														1		1							1	3		1	9
I												1			1				1	10					1								1	1			16
J																	1				10					1	1								1		14
K																																1					1
L					1						2			1			1					1							1	1		2		1			11
M								5																1	3												9
N								1		1			1												2	1					1						7
O				1											1		1		1								13			1						1	19
P	1					1												6																1			9
Q	4			1			1																						2					1			9
R																1																					1
S						1																			1	1	1					1		2			7
T								1											1						1	1			1		1		1				7
U																						1	1			1	1										4
V																									14	3								1			18
W					1													1							1												3
X											1														1												2
Y																								2		1			2			2		1			8
Z																			2				1						1					1			5
0										1					1		4									7			6					5		1	25
1						1			3			1				1			3	2					1				2	3	28	1		3			49
2																	1																				1
3																		1													1	2		2	1		7
4																													1					2			3
5																																	1				1
6		1								1																											2
7																									1	4			2			1					8
8				1															1		1											1	1				5
9																													1								1
Σ	6	2	0	3	7	5	3	8	3	4	4	2	1	1	3	5	8	10	10	13	12	2	2	4	26	21	17	1	20	5	31	14	10	25	2	4	294

FONT : HUDDLESTON 7x9

Figure 114. Confusion Matrix for 7 × 9 Huddleston Font

S\R	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A																																					0
B				1																																	1
C							2								1																						3
D																								1								1					2
E																		1																1			2
F		1		1	1						2																							1			6
G																																					0
H																																					0
I																				11				1							1	1					14
J			1			1	1							1							5									5	1						15
K																																					0
L					3		1							1				1			2					2							1				11
M														3							1			1													5
N																											1										1
O				1													3										11			1				2			18
P										1							1	4								1			1							1	9
Q																																					0
R																																					0
S							1			1																7						2		1			12
T									1	1									1						4								1	2			10
U												1											2														3
V																					3			1	7	1											12
W																																					0
X																										1											1
Y										1																						1			1		3
Z							1																						1					1			3
0										1					5		5									7			3		2			3		1	27
1									2		1									2				1		1			2	4	20	1		2			36
2																														2		1					3
3						1																										4					5
4																			2																		2
5																																					0
6																																					0
7																									1	3						3					7
8																	1																1			1	3
9																																					0
Σ	0	1	1	3	4	2	6	0	3	5	3	1	0	5	6	0	10	6	3	13	11	0	2	5	12	23	12	0	7	12	24	14	3	13	1	3	214

FONT : HUDDLESTON 9x11

Figure 115. Confusion Matrix for 9 × 11 Huddleston Font

S\R	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A																																					0
B																		1																			1
C					1																													1			2
D					1																																1
E						1	1											1												1							4
F					3					1	1					2		3	1	1					1	1				1	1			1			17
G						2									2												2						2				8
H										1		1											1														3
I												1				1			1	3											1						7
J											1										8		1			1											11
K																																					0
L					2	1					2															1			2								8
M		1									1			2																							4
N																																					0
O																											11							1			12
P		1				2	1											6																			10
Q																													1								1
R																																					0
S			1																										1								2
T									5										1						1		1	1	1				2	1			13
U																									1		1										2
V																					2			1	23												26
W																																					0
X														1								1															2
Y														1							2	1		4													8
Z																								1					1					1			3
0		1		1											3		5							1	1				3					1	1		17
1						1	1		2		1		2	1				2	1		1			1		1			5		18		1	2			40
2																														2							2
3																									1						1						2
4																													1				1				2
5																																		1			1
6										1																											1
7							1																			1		1									3
8		3																															1				4
9																																					0
Σ	0	6	1	1	7	7	4	0	7	3	6	2	2	5	5	3	5	13	4	4	13	2	2	8	28	5	15	2	15	4	21	0	7	9	1	0	217

FONT: HUDDLESTON 7x9 (=5x7)

Figure 116. Confusion Matrix for 7 × 9(= 5 × 7) Huddleston Font

S\R	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A																																					0
B																		1																			1
C				1																																	1
D																																					0
E																							1							1			2		1		5
F	1				1													1	1							1								2			7
G																																					0
H																																					0
I																				8				1	1						1			1			12
J																			1		5	1	1		1					3							12
K										1																											1
L		1			2		1											1			1		1			1			2								10
M														1																							1
N													1																								1
O				2													1		1				1	1			14										20
P						1												4																			5
Q																		1																			1
R																																					0
S																										2			1								3
T		1							1	1															4			1	1								9
U																							1			1											2
V																					3		1	3	5												12
W																																					0
X																																					0
Y																						1		1		1											3
Z																														1				1			2
0															1			1						1		7			2	1				3			16
1			1		1			1	2			1	2	1						3			1	2	1	1			3	1	12	4	1				38
2																																					0
3																																					0
4																																					0
5																																					0
6																													1					1			2
7																		1															1				2
8																																					0
9																				1							1										2
Σ	1	2	1	3	4	1	1	1	3	2	0	1	3	2	1	0	1	10	3	12	9	2	7	9	12	14	15	1	10	7	13	4	4	8	1	0	168

FONT : HUDDLESTON 9x11 (=5x7)

Figure 117. Confusion Matrix for 9 × 11(= 5 × 7) Huddleston Font

S\R	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A																		2																			2
B				17																														1			18
C					2		5	1																							4						12
D															1																			1			2
E							1																						1	1			13		1		17
F	2				1											1																	1				5
G						1																											3				4
H	1																							1													2
I																				10					1												11
J																														1							1
K																																					0
L			1	1						1											2		6										8		1		20
M														1						2			2							1			1	1			8
N						1															2		5	3													11
O				8			1																				3						1		2		15
P	5			1											1			1																			8
Q				3			5								9								2			1	5						4				29
R	2																																				2
S																																46	1				47
T				2		1		1	3	2											2				4									2	1		18
U															1							5	10										1				17
V																								1	50										1		52
W													2							1	1	1			2												7
X																						1			1												2
Y																						4		1													5
Z																													13								13
0	1		1	2	1										1		1							3		17			21	1				7	1		57
1									7											1			1				1						1		1		12
2																										3								2			5
3																																					0
4																					1		1														2
5																			8								1						5			1	15
6							11																									2					13
7																										6			24								30
8	1	13					1									1	1	1	2					1			1		4	1		1	5			4	37
9										1									8													1		1			11
Σ	12	13	2	34	4	3	24	2	10	4	0	0	2	1	13	2	2	4	18	14	8	11	27	10	58	27	11	0	63	5	4	50	44	15	8	5	510

FONT : MAXIMUM DOT 5x7

Figure 118. Confusion Matrix for 5 × 7 Maximum Dot Font

S\R	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A																		2																			2
B				7	1														1							1				1						1	12
C		1			2		2					1							1										1				3		1		12
D		1										1			2																						4
E			2				2																						1	2			7				14
F	1				5											2		3															2				13
G		1																						1									3				5
H														1				1					1														3
I																				11	1																12
J																																					0
K																																					0
L							1												2		1		2						1		1		2				10
M														1									2														3
N																																					0
O			1	2													10			1				1		1	8		2			1	1	3	2		33
P	2	1				1												8																			12
Q				1			5								6			1	1			4	3	1	1		4		3	1				1		1	33
R																																					0
S																																53					53
T									4																2				2			1		2			11
U										2												2	12		1				1								18
V								1															1	1	27												30
W					1								2								1	1															5
X																										1											1
Y																						4		1													5
Z																													1								1
0				2											1		1					2		3	1	14			23						8		55
1									2											1			1						2			1		2			9
2																										25								2			27
3																																					0
4																1						1															2
5																			4																		4
6							13												2										1			4					20
7																										13			14								27
8	1	8		3	2										2				1				1	2		1			5	2			2	3		2	35
9																1			6											2		1	1				11
Σ	4	12	3	15	11	1	23	1	6	2	0	2	2	2	11	4	11	15	18	13	3	14	23	10	32	56	12	0	57	8	1	61	21	13	11	4	482

FONT: MAXIMUM DOT 7×9

Figure 119. Confusion Matrix for 7 × 9 Maximum Dot Font

S\R	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A																																					0
B				10																										1			1		2	1	15
C					4		3																														7
D															1																						1
E			1			1																							1	1			3				7
F																																1					1
G																																2	13				15
H																																					0
I										2										6									1								9
J									1																												1
K																									1												1
L			1		1																		7	1					1		1		5				17
M																																					0
N																																					0
O				2			1					1					9				1						7							2	2		25
P																		4																			4
Q							2								7							1	1			1	5			1					1		19
R																																					0
S																																45	2				47
T									5																1												6
U					1																		16												1		18
V																								2	44												46
W																																					0
X																						3															3
Y																						2			1	1											4
Z																																					0
0	1			1		1	1								2									2		21			21					2			52
1									1											1																	2
2																										21											21
3																																					0
4																																					0
5																			2												1						3
6							4																							1					1		6
7																										5			26								31
8	5	4				1	2	1						1			2									1	2		2	1			5			3	30
9																			5											1		1			3		10
Σ	6	4	2	13	6	3	13	1	7	2	0	1	0	1	10	0	11	4	7	7	1	6	24	5	47	50	14	0	52	6	2	49	29	4	10	4	401

FONT : MAXIMUM DOT 9 x 11

Figure 120. Confusion Matrix for 9 × 11 Maximum Dot Font

S\R	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A																		11								1											12
B				5												1														1							7
C					1		1					2																	1			1	3				9
D															2												1										3
E																		1												1			4				6
F	3	1			5													1																			10
G																																	3				3
H																				1			1			1					1						4
I																				7			1							1							9
J															1																						1
K																																					0
L			2																						1				1	1							5
M															1							1															2
N																																					0
O				3													6					1		1			9		3								23
P																		4											1			1					6
Q				1			2								10											2	1						2				18
R																																					0
S																																58					58
T								1	6															1		1			1				2				12
U																							6														6
V																									25												25
W																																					0
X																						2															2
Y																						2		1													3
Z																													5								5
0															1		1	1					1			18			20					5			47
1									2																				1			1		1			5
2																										12								6			18
3		1																																1	4		6
4																																					0
5																			4																		4
6							8												1													2					11
7																										5			13								18
8	5	7		1			2								2			1	1				2		1				3	1			3				29
9																			4													1					5
Σ	8	9	2	10	6	0	13	1	8	0	0	2	0	0	17	1	7	19	10	8	0	6	11	3	27	40	11	0	49	5	1	64	17	13	4	0	372

FONT : MAXIMUM DOT 7x9 (=5x7)

Figure 121. Confusion Matrix for 7 × 9(= 5 × 7) Maximum Dot Font

S\R	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A																		2																			2
B			1	7								1																				1		1			11
C					4	1	2																				1						1				9
D															2																						2
E											1							1																			2
F	1										2							3																			6
G																																	1				1
H														1							1																2
I															1					5																	6
J							1																														1
K																																					0
L					2			1			1			1																			1				6
M																																					0
N																																					0
O				1			1			1	1						2			1							3		1								11
P	2																	3																			5
Q															4												1								1		6
R																																					0
S																																49	1				50
T									4																2												6
U							1															1	5	1										1			9
V																				1				6	44												51
W					3																																3
X																						2			1												3
Y							1															1		2								1					5
Z																													1								1
0				1											3	1										13			14				1	2			35
1																																1	1				2
2																										21								3			24
3																																		1	1	2	4
4																																					0
5																1			5														2				8
6		1					6																									1					8
7																										7	1		14						1		23
8		6		1		1									1		1	1						2					3	1	1	1		1			20
9																			2													2					4
Σ	3	7	1	10	9	2	12	1	4	1	5	1	0	2	11	2	3	10	7	7	1	4	5	11	47	41	6	0	33	1	1	56	8	9	3	2	326

FONT : MAXIMUM DOT 9x11 (=5x7)

Figure 122. Confusion Matrix for 9 × 11(= 5 × 7) Maximum Dot Font

S\R	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A							1	4												1				4									1	2			13
B				11			1	1														1										1	2			2	19
C				1			3																														4
D			1																																		1
E				1																						1							1				3
F					3									1		1		2											1			2					11
G								2																									2				4
H														1									1	1							4						7
I																				18					1	1		2									22
J																					7	4	1	1	1	4			1					4			23
K																							1														1
L					2		1	1		2	1					1			2	3		1	1	1	1	6		2	1		1			5			32
M					1			4						5									1	2										1			14
N							1	5		2			2										1	1						1			1				14
O				3	1												10			1		1	1				9		1				2	2			31
P		1		4		1	1											7											1				1		1		17
Q	7			5			3				1				12				1				1	1	2	3	1			1			1	2	1		42
R																																					0
S			1		1					1						1		1		2						2	1			10		2	5	6			33
T		1			1				5										2			1			2	1		2	1	1				8	1	1	27
U		1								1												14	2	1	3	1				1							24
V									1							8					2			1	10	2						1		2			27
W								1						2										1		1					1						6
X											1										1				2	1											5
Y											1		1									3		4										5			14
Z																													11					5			16
0	1		2	1		1	5			3				1	12		6	1	6		1	2		2	1	3			1			2	8	4	1		64
1				2	3		1	1	7	5				2					1	6			1	5	3	1			2	4	7	2	4	8		1	66
2													1										1			6								1			9
3																			1						1				2				1	1			6
4																										1											1
5																																					0
6							1																	2		2								2			7
7																										3				2							5
8		1								1				1																		1	10	1			15
9																								1		2			7					16			26
Σ	8	4	4	28	12	2	18	19	13	15	4	0	4	13	24	11	16	11	13	31	11	26	12	28	27	41	11	6	29	20	13	11	39	74	4	4	606

FONT : MAXIMUM ANGLE 5x7

Figure 123. Confusion Matrix for 5 × 7 Maximum Angle Font

S \ R	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A																																					0
B						1													1													1					3
C							2				1															1											4
D																			1																		1
E							1												1																		2
F		1			4			1										1								1					1		1	3			13
G																										1							1				2
H											2													1		1						1		2			7
I		1			1					1									5	11	1			1	1				1		1						24
J			1														1		1		10	9	1	1	1	2			1			1		1			30
K																																					0
L			1				1		2		1								2	3			1	2	1			2	2		2		2	5			27
M														4											1									1			6
N		1											1																1								3
O				1	1			1					1				3		3	1	1	1		1		4	7			1			1				27
P							1											4																			5
Q	1						1								5							1		2		3	9									1	23
R																																					0
S				1														1											1					1		1	5
T									4	2									4						1					1	1	1	1	3			18
U										4												12	1		3	1											21
V																					1			1	3	1						1	1				8
W													1													1											2
X								1																	2												3
Y																				2		1		4									1	1			9
Z																													1	1				2			4
0	1		2												1		7		3			2		5	1	6			9	1			5	3			46
1					1			2	2		2	1							4	9	1	3		4	3	2				5	13	1	1	2			56
2																																					0
3																1															1					1	3
4																																		1			1
5																															1						1
6																			1																		1
7																				2						4		1	1				4				12
8		2																	1														2				5
9																																		1			1
Σ	2	5	4	2	7	1	6	5	8	7	6	1	3	4	6	1	11	6	27	28	14	29	3	22	17	28	16	3	17	9	20	6	20	26	0	3	373

FONT: MAXIMUM ANGLE 7x9

Figure 124. Confusion Matrix for 7 × 9 Maximum Angle Font

S\R	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A																														1							1
B																														1							1
C				1	1		2				4								1										1				1				11
D																														1							1
E																			1											1							2
F		1			6													1													1		1				10
G						1																				2											3
H																													1				1				2
I																			1	18			1		1	1		2		1	1						26
J																					9	12	1	1		6			1	3		1		2			36
K										1																					1						2
L				1					4										3	8				2	1	1		1	1	2	2			4			30
M																								1		1											2
N																						1															1
O					1												3								1	5	3		1			2				1	17
P		3																8															1				12
Q							3											1	2				1			2				3							12
R																																					0
S				1														1						1						1	1	1		2			8
T		1							2										1						2			2			2		2				12
U										2												17		1	2	2				1							25
V																							2	1	11						1						15
W						1																		2													3
X																									2												2
Y																	1	1		1		1	1			2						1					8
Z																													1	1							2
0			1		1	1	1										2	1	4	2		1	1	9	1	5			1	1			2	5		1	40
1							1		4	1									1	15		1			1	3				12	8			3			50
2																																					0
3																																					0
4																																1	1				2
5																			1												1						2
6																																		1	1	1	3
7											1														3	1				4			2				11
8																	1								1					2			1				5
9																																		1			1
Σ	0	5	1	3	9	3	7	0	10	4	5	0	0	0	0	0	7	13	15	44	9	33	7	18	26	31	3	5	7	35	18	6	12	18	2	2	358

FONT: MAXIMUM ANGLE 9x11

Figure 125. Confusion Matrix for 9 × 11 Maximum Angle Font

S\R	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A																														1	1						2
B																														1			1				2
C				2	1	1	10																1			1											16
D		1																								1			1	1							4
E	1																					1												1			3
F				1	3														1	1				1		1								1			9
G																										1								1			2
H										2													1							2	2						7
I		1		1	1														1	16				3	2	1				1	1	2					30
J	1				1														4		8	9	1	2	1	2				7	2			2			40
K																				1						1											2
L	1				4						3			1				1	2	3				1		1		1	1	4	5		1	3			32
M						1								2											3						1						7
N													1											1		2											4
O	2						1										5		1		1			2	1	6	7		1	2		1					30
P		1																2						1													4
Q	2				1		1								9			1	3					2		5	2		1	1	1		1	1			31
R																							1			1											2
S																				1				1		1			1						1		5
T		1				2			1															2	1	1		1		1	2	1		1	1		15
U										3				1						1		14	1	3	1	4											28
V	1																1			1	4			4	4	5											20
W																								3		1											4
X		1																							3					1			1				6
Y		1			1															1				2						1			1	2			9
Z		1																											2	1				2			6
0	1			2											2		6		3			1		4	1	11			4	2	1		1	11			50
1		1			5				1					1					3	8		1		5	5	6			1	5	14	2	2	4			64
2																														1	1					1	3
3		3	1																1	2													1				8
4																														2						1	3
5											1																						1				2
6																										1								3			4
7	1																			3			1	1	2	5				1	4	1					19
8	3	2					1	1									2					1				1						1	6				18
9																											1		1			1		2			5
Σ	13	13	1	6	17	4	13	1	2	5	4	0	1	5	11	0	14	4	19	38	13	27	6	38	24	59	10	2	13	35	35	9	16	34	2	2	496

FONT: MAXIMUM ANGLE 7x9 (=5x7)

Figure 126. Confusion Matrix for 7 × 9(= 5 × 7) Maximum Angle Font

S\R	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9	Σ
A																																					0
B					1																																1
C							2				3								1					1		2											9
D						1																															1
E																									1					1							2
F		2		1	1														1															1			6
G																																	1				1
H														1									1	1													3
I				1	1	1		1			1								1	15				2	2												25
J					1																8	13	1	4	5	3											35
K										1																											1
L					2	1	1	1		1	1			1					1	3			1	5		2		1	3		1	1	1	1			28
M														1																							1
N																																					0
O					1						1						2							2	1	2	6		1								16
P																		4																			4
Q															1								1	3									1				6
R						1																															1
S																		2								1								1			4
T		2							10						1			1	5			1	2	3					2	1				1		1	30
U					1					3												17	2	5	3	2						1					34
V																							1	2	12	1											16
W																										1											1
X																		1				1			4	1								1		1	9
Y																				2	1			3				1		1		1		1			10
Z																																		3			3
0	1	1								1	1				2		4		3			1		11	2	3			5				2	6			43
1		1							6	2	1								4	5			1	6	6	6				4	7	2	2	4			57
2																							1														1
3																											1										1
4																								1						1		2		2			6
5																														1			1				2
6																																2		2	1		5
7																						1		1	2	2			1	1							8
8																																	1				1
9																																		1			1
Σ	1	6	0	2	8	4	3	2	16	8	8	0	0	3	4	0	6	8	16	25	9	34	11	50	38	26	7	2	12	10	8	9	9	24	1	2	372

FONT: MAXIMUM ANGLE 9x11 (=5x7)

Figure 127. Confusion Matrix for 9 × 11(= 5 × 7) Maximum Angle Font

IX. EXTENDED PREDICTION MODEL

The prediction equations discussed earlier were based on photometric and performance data measured for a variety of dot-matrix configurations. The range of spatial frequencies used in the regression procedure which yielded the predictive metrics (Section V) was approximately 4-17 cyc/deg. As the validation study (Section VI) showed, and later research has verified, the range of spatial frequencies used to generate the original metrics is insufficient to analyze many commercially available displays. For example, the Owens-Illinois DIGIVUE-type plasma panel has about 23.6 dots/cm horizontally. This corresponds to a fundamental spatial frequency of 20-30 cyc/deg at normal viewing distance.

The verification study (Section VI) revealed that the original metrics were poor predictors of subject performance on the DIGIVUE display due to the restricted range upon which the metrics were based. In an attempt to eliminate this shortcoming, an extended prediction model has been derived for Tinker SOR and menu search performance.

Method

To extend the range of the original prediction equations, it was necessary to include photometric and performance data from higher spatial frequency displays in the pool of regression variables. Such data were already available from both the simulation study as well as the verification phase of this research. The verification phase used actual SELF-SCAN and DIGIVUE displays instead of dot patterns designed to merely simulate these displays. The availability of these data allowed the extended models to be generated without the necessity of additional data collection from more subjects.

The actual equation generation was accomplished exactly as it was for the original metrics. The same pool of predictor variables was subjected to stepwise linear multiple regression analysis using the Statistical Analysis System (SAS) (Barr, *et al.*, 1976) software on the University computing system. This time, however, the data submitted for analysis originated from the following studies:

1. The original dot-matrix study upon which the first metrics were based (Section III),

2. The simulation study which was used as a predictive validation of study (1) (Section V), and

3. The verification study which used real displays instead of simulations (Section VI).

Sources (2) and (3) contained data from displays having fundamental spatial frequencies in the 20-30 cyc/deg range.

Results

The data pool allowed the generation of extended metrics for the Tinker SOR task and the menu search task. It was not possible to generate an equation for the random search task, since no performance data were taken for this particular task in the verification study. (The reason for this omission has been described earlier.) One adjustment was necessary in the Tinker SOR data from the verification study, however. It was noted that in both the original and simulation studies, the baseline reading speed was measured using the Tektronix 4014-1 terminal as the display device. In the verification study, the baseline reading speed was measured using typewritten passages on white paper. This procedure allowed the baseline reading speed to be determined with each subject viewing the same type of display (the typewritten page) regardless of the display which was viewed in the experimental trials. Unfortunately, this procedure also caused the adjusted reading times to be substantially shorter, since the baseline passages on the typed sheets took relatively longer to read than did the same passages on the Tektronix display. To account for this difference, a constant 0.8 s was added to the adjusted reading speed for each display in the verification study. This 0.8 s is the difference between the mean baseline reading times for the two baseline techniques.

The resultant prediction equations and their R^2 values are shown in Table 37. The meaning of each variable name is the same as for the original equations (Table 25).

Discussion

Several features of the extended prediction equations should be noted. First, and perhaps most important, these equations apply to dot-matrix displays in which the fundamental spatial frequency of the repetitive dot pattern falls between 4-30 cyc/deg. This virtually doubles the usable frequency range of the equations.

The next notable thing about the extended equations is that the range doubling was accomplished with very little loss of correlation between observed performance and performance predicted by the regression

TABLE 37. Extended Predictive Equations

Task	*Metric and Related Information*
Tinker SOR	Adjusted Reading Time (s) = 5.74 + 0.311(HFREQ) + 2.479(HMOD) + 4.365(HLOG) - 14.973(HFLOG) + 1.112(VMLOG)
	Correlation Coefficient R = 0.72
	R^2 = 0.525
	Asymptotic R^2 = 0.637
Menu Search	Search Time (s) = 7.27 + 0.027(HDIV) + 2.159(HLOG) + 5.916(VFLOG) - 0.339(VMTFA) - 0.054(VRANG) + 5.487(VMLOG)
	Correlation Coefficient R = 0.71
	R^2 = 0.500
	Asymptotic R^2 = 0.575

equations. The extended equations correlate 0.72 and 0.71 with observed performance. These compare closely with the 0.76 and 0.69 correlations, respectively, obtained in the original equations.

Some cautionary notes must be added pertaining to the interpretation and use of these extended equations. First, note the predominance of horizontal terms in the Tinker SOR equation and of vertical terms in the menu search equation. It would be easy to hypothesize, on the basis of these equations, some psychophysical process which depends upon horizontal information for reading and vertical information for searching columnar material. Although such hypotheses might have heuristic validity, no such conclusions can be safely supported by these prediction equations. Past analyses have revealed a high correlation between horizontal and vertical terms in these data. Thus, the statistical algorithm which includes a vertical term and excludes the corresponding horizontal term may well be basing this decision on either serial position in the variable pool or very minute quantitative differences.

Second, the most important caution to observe when using these equations is to understand that no *external validation* has been attempted. This means simply that all the data in our possession pertaining to these displays were used to generate the extended equations. After the equations were generated, no performance data were collected on displays *other than those used to generate the equations*.

In contrast to this set of generated equations, the original equations were obtained using data from an extensive dot-matrix display experiment. After the equations were generated, more performance data were gathered in the simulation study. The simulation study used not only different subjects than those used in the original study, but different dot shapes and sizes as well. After the simulation study, the actual performance of subjects was compared to the performance values predicted by the equations. This is known as *external validation* and gives some idea of the generalizability of the equations.

On the other hand, there is no reason to believe that the extended equations will not generalize as well as, or better than, the original equations, although no objective test of this validity has been undertaken.

It is believed that the extended predictive metrics described in this section are very good predictors of relative observer performance using a wide variety of dot-matrix displays. As such, they represent the best available *empirically derived* measures of dot-matrix image quality. They should not, and cannot, be applied to non-dot matrix characters, or to dot matrices the fundamental spatial frequency/ modulation of which is below visual threshold. Thus, for example, a double-electorde prototype Owens-Illinois DIGIVUE, with 23.6 (double) dots per centimeter cannot be analyzed by these equations simply because the fundamental spatial frequency is 59 cyc/deg (47 dots/cm at 71 cm viewing distance), which is below visual threshold at the displayed modulation of those dots.

X. DISCUSSION

The previous sections have presented a large amount of empirical data, prediction equations, recommendations, and descriptions of representative observer tasks. Taken together, these data are extremely internally consistent and simultaneously in agreement with the few pertinent previous studies. Several of these consistencies and comparisons are worthy of additional discussion, as are some of the questions developed and not answered by this research program.

Performance Measures and Tasks

One of the earlier studies in this series (Section II) was designed to compare several single-character response measures for the purposes of (1) estimating relative sensitivity of the measures, and (2) specifying a measure to be used subsequently. Fortunately, there were generally high correlations among the various measures so that we felt justified in using accuracy (or percent correct), tachistoscopic recognition accuracy, and response time measures in subsequent studies. It is believed that a selection among these three measures is not critical to the conclusions of a well defined experiment in this general problem area. These measures produced consistent results in Sections IV, VII, and VIII.

In a desire to create tasks more complex and representative than single character recognition in a specified display location, we selected the Tinker SOR, random search, and menu search procedures. The Tinker test, as modified and used in these experiments, has proven to be sensitive and consistent. We are convinced it is a good experimental task to employ, so long as each subject is not requested to read more than 50 or so of these rather simple passages. Beyond that point, the task becomes noticeably boring and performance variability may increase.

The Tinker SOR test is representative of a reading task in which the operator is attempting to obtain information from a contextual display of related, partially redundant information. As will be summarized below, this task is facilitated by displaying relatively small characters with moderate to high dot modulation.

By comparison, the random search and menu search tasks are representative of siutations in which the observer must locate a symbol or group of symbols which are unrelated to other displayed information. Redundancy is virtually zero, and location uncertainty is maximum. This type of task is facilitated by characters which are much larger, have greater dot modulation, and larger dot sizes. In addition, as an experimental task, the menu search is more predictable with small intersubject variability than is the random search task. Thus, for future research, the menu search paradigm is recommended over the random search.

Agreement with Previous Research

Where comparisons can legitimately be drawn, the results of these experiments largely agree with previous isolated studies. On a variable-by-variable basis, such agreements and overall results are summarized below.

Character size. Previous research had recommended character sizes of at least 12 minutes of arc for 85% character recognition and 16.4 minutes of arc for 97% recognition for single, clearly defined, nonblurred characters having a modulation of at least 88% (Howell and Kraft, 1959). Shurtleff (1974) and Giddings (1972) similarly recommended 22 and 21.5 minutes of arc angular subtense, respectively, as being optimal, although Howell and Kraft (1959) indicated 27 minutes of arc was needed for blurred characters and Shurtleff, *et al.* (1966) suggested 36 minutes of arc might be needed for raster-scan characters.

The present results clearly indicate that, for high modulation characters, no further improvements are obtained beyond 11 minutes of arc for single character recognition in a known display location (Section II). If the modulation is reduced to the order of 40%, then larger (e.g., 17 arcminute) characters are needed even if there is some contextual effect (Section IV).

To minimize reading times, 25 minutes of arc seems maximal for character vertical subtense (Sections III and IV). To minimize search time, however, larger characters prove better, as shown in Section VI for the SELF-SCAN characters which subtended 63 minutes of arc.

Dot size. Smaller dot sizes (e.g., 0.76 mm) are best for reading contextual material, while larger dots (and therefore generally larger characters) are best for search tasks. A 1.5 mm dot is better for a search task than is a 0.75 mm dot, while the converse is true for a reading task. A reasonable compromise, if the display is to be used for both types of task, is a dot with diameter on the order of 1.0 to 1.2 mm.

Dot shape. The more square the dot, the better the observer can perform reading, search, and single character recognition tasks. Elongated dots are measurably poorer.

Dot spacing. The present results clearly indicate that performance increases as interdot spacing decreases. A dot spacing/size ratio of 0.5 is superior to one of 1.0 or 1.5. This result essentially agrees with that of Ellis, *et al.* (1974), who found that performance was better with a 0.5 ratio than with a 1.0 ratio. In general, the data suggest that the closer a dot matrix character approximates a continuous stroke character, the better will be the observer's performance.

Dot luminance/modulation. These parameters are, of course, not independent of one another or of the ambient illuminance. What matters most to the visual system, for the most part, is the dot modulation, as long as its luminance is above a reasonable level, say 25 cd/m^2.

Howell and Kraft (1959) recommended a modulation of 94%, but suggested that 88% was acceptable. The present results indicate that 75% for words (letters in context) is equivalent to about 90% for noncontextual material. Thus, their previous results highly agree with ours and point out that single symbols and characters must have higher modulation to be 85% recognizable than must partially redundant characters. In high ambient conditions, appropriately designed filters and glare shields become mandatory. If ambient illuminance is controllable, a relatively low level of 20 to 50 lux is desirable for maximum display information transfer.

Font selection. Section VIII data indicate that the Huddleston font is superior to other fonts for a relatively small (14.4 arcminute)

5×7 matrix, but that the Lincoln/Mitre font is to be preferred for larger matrix sizes of the same or larger character size (up to 22.9 arcminutes).

This result is important for software/firmware character generators, as well as for matrix size selections. It agrees with the results of Vartabedian (1971) and Shurtleff (1974), who concluded that a 5×7 matrix size was inferior to larger (7×9 or 7×11) matrices.

These results apply only to capital letters and numerals. If both upper and lower case letters are required, a matrix larger than 5×7 is required to display the descenders on the letters g, j, p, q, and y. Larger matrices are also required for some symbols, subscripts, superscripts, italics, and perhaps other unique needs.

Image Quality Metrics and Prediction

In Section V we presented an empirically derived, linear multiple regression prediction equation for each experimental task. These equations were subsequently validated with production displays in Section VI. The relationships between predicted and actual search and reading performance levels were quite satisfactory and led to a logical acceptance of the models, which were subsequently extended to greater ranges of the predictor variables by the process described in Section IX.

Although no subsequent cross-validation studies have been conducted on the Section IX model equations, these equations have been applied to photometric scans made from several additional dot-matrix displays under a variety of circumstances. The predicted observer performance levels are heuristically reasonable, logically ordered, and well behaved. Thus, we have little reason to doubt that the models presented in Section IX are good predictors of search and reading performance with dot-matrix displays. Of course, further research validation is quite desirable.

Photometric Measurement

Photometric measurement techniques have been discussed in some detail throughout this report. This attention to detail has been deliberate, for we strongly believe that such measurements, *at the display surface*, are critical to the development of an understanding of image quality concepts and to improved display design. Visual inspection and area measurements of display luminance are totally inadequate. The visual system responds differentially to dot edge gradients, dot irregularities, electrode patterns, and the like. Only by such microphotometric measurement can data be obtained on the physical variables of the display which affect observer information extraction, as demonstrated in Sections IV, V, and VI.

One- vs. *Two-Dimensional Photometry*

In all photometric measurements described in this report, one-dimensional scans were made, either vertically or horizontally or both. It is also possible to scan a display surface in both dimensions, creating a two-dimensional array of luminance information. Such an array can then be analyzed in a variety of ways, including a two-dimensional Fourier analysis. There is a good possibility that the coefficients of a two-dimensional Fourier analysis might serve as predictors of operator performance, following the argument offered by Pantle (1974). Such an approach is recommended in future research efforts.

Remaining Research Questions

While considerable progress has been made in the need to predict and understand information extraction from dot matrix displays, several research questions and recommendations have also surfaced. These are noted here for the benefit of future research planning.

Font optimization. Our results have shown that there is a substantial interaction among matrix size, character size, and font for numerals and capital letters. We know virtually nothing about this interaction for symbols, lower case letters, subscripts, superscripts, etc. Such research is clearly and urgently needed, even though the proliferation of various character styles continues unabated with the development of new display hardware.

Model development. While the current prediction equations (Section IX) are useful and quite valid, they can probably be improved upon by two-dimensional photometric analysis, as suggested above. They should also be revised to include displays which have dot fundamental spatial frequencies above 50 cycles/degree, i.e., characters which visually appear to be "stroke" characters. The present equations cannot be applied to such displays.

Paging displays. In several applications, such as menu lists and word processing systems, the display cannot present all pertinent information simultaneously. To overcome this limitation, the display is typically scrolled, vertically or horizontally. No data exist on the effect of scroll rate on information extraction performance. Interactions with character size, matrix size, information density, and other variables should be anticipated. Such research is needed and recommended.

XI. SUMMARY AND DESIGN RECOMMENDATIONS

Taken as a whole, the results of these experiments and analyses offer strong guidelines for the design of dot-matrix displays for maximum information transmission. The results further show that a single point design is quite unlikely to be optimal for various observer tasks; rather, the display should be optimized for the type of task required of the user. For purposes of generalization and recommendation, suggested design guidelines will be offered for two generic types of tasks: (1) reading of partially redundant, contextual material in which each character is partially predictable from the adjacent characters and context of the material, and (2) noncontextual displays, in which the observer is (typically) searching for a single character, or small group of unrelated characters, on a display containing a large number of such characters.

Design recommendations, on a variable-by-variable basis, are given in Table 38. Most of these recommendations are derived from the data and results presented in this report. Where such data have not been generated specifically, previous experimental results have been applied as guidelines. As in all design recommendations, these values are not defensible to better than 10% or so. They should be applied intelligently to any given design application, with a full understanding of appropriate human engineering, component design, and system integration principles.

TABLE 38. Design Recommendations for Dot-Matrix Displays

Variable	*Contextual Display*	*Noncontextual Display*
Dot Size[a]	0.75 mm	1.2 to 1.5 mm
Dot Shape	Square	Square
Dot Spacing/Size Ratio	≤ 0.5	≤ 0.5
Matrix Size[b]	7×9	9×11
Character Size[a]	16 to 25 arcminutes	1.0 to 1.2 arcdegree
Dot Luminance	≥ 20 cd/m^2	≥ 30 cd/m^2
Dot Modulation	$\geq 75\%$	$\geq 90\%$
Ambient Illuminance	≤ 125 lux	≤ 75 lux
Font[b]	Lincoln/Mitre	Lincoln/Mitre

[a]Assumes given levels of other variables.

[b]Numerals and upper case letters only.

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APPENDIX A

CELL MEANS

5.4 lux

Element Size(mm)	Element Shape[a]	Interelement Spacing/Size Ratio	Reading Test(s)	Random Search(s)	Menu Search(s)
0.76	S	0.5	1.13	6.68	5.37
0.76	S	1.0	1.58	6.99	5.41
0.76	S	1.5	2.71	5.58	6.89
0.76	H	0.5	1.72	6.34	6.44
0.76	H	1.0	1.85	5.15	5.93
0.76	H	1.5	2.23	6.23	6.52
0.76	V	0.5	1.80	8.84	6.22
0.76	V	1.0	2.08	7.67	6.40
0.76	V	1.5	0.86	5.95	6.34
1.14	S	0.5	0.61	4.83	4.17
1.14	S	1.0	1.08	5.32	5.00
1.14	S	1.5	2.23	5.54	4.99
1.14	H	0.5	0.61	6.51	5.69
1.14	H	1.0	2.47	4.89	5.22
1.14	H	1.5	3.96	8.92	6.88
1.14	V	0.5	1.73	5.50	5.96
1.14	V	1.0	1.46	5.58	5.80
1.14	V	1.5	2.13	4.54	5.14
1.52	S	0.5	1.43	6.60	5.78
1.52	S	1.0	2.63	4.36	5.68
1.52	S	1.5	3.01	4.64	5.60
1.52	H	0.5	2.24	6.94	5.77
1.52	H	1.0	2.93	6.15	6.03
1.52	H	1.5	3.42	5.53	6.55
1.52	V	0.5	1.89	5.36	4.96
1.52	V	1.0	2.05	4.38	5.62
1.52	V	1.5	2.03	5.38	5.58

[a]S = square; H = horizontally elongated rectangle; V = vertically elongated rectangle.

700 lux

Element Size (mm)	Element Shape[a]	Interelement Spacing/Size Ratio	Reading Test(s)	Random Search(s)	Menu Search(s)
0.76	S	0.5	0.48	7.25	6.01
0.76	S	1.0	1.48	9.31	6.04
0.76	S	1.5	2.47	7.49	6.63
0.76	H	0.5	2.01	12.60	7.14
0.76	H	1.0	2.17	9.28	6.85
0.76	H	1.5	2.75	6.32	6.33
0.76	V	0.5	2.13	8.35	6.04
0.76	V	1.0	2.98	14.05	7.74
0.76	V	1.5	4.86	21.53	7.68
1.14	S	0.5	0.66	5.52	4.77
1.14	S	1.0	1.54	5.88	5.60
1.14	S	1.5	3.29	8.05	5.31
1.14	H	0.5	1.13	7.71	5.46
1.14	H	1.0	2.80	7.60	5.34
1.14	H	1.5	1.85	8.90	6.98
1.14	V	0.5	1.17	8.58	5.36
1.14	V	1.0	1.89	7.56	6.00
1.14	V	1.5	1.74	5.93	5.28
1.52	S	0.5	1.31	7.02	5.63
1.52	S	1.0	2.32	6.16	5.18
1.52	S	1.5	2.92	7.69	6.05
1.52	H	0.5	1.94	8.36	6.27
1.52	H	1.0	3.67	8.84	6.13
1.52	H	1.5	4.40	7.52	7.04
1.52	V	0.5	1.54	6.06	5.47
1.52	V	1.0	2.41	6.41	5.10
1.52	V	1.5	2.05	7.27	6.36

[a]S = square; H = horizontally elongated rectangle; V = vertically elongaged rectangle.

APPENDIX B

WORDS AND ANAGRAMS

FAMILIAR WORDS	ANAGRAM	UNFAMILIAR WORDS	ANAGRAM
ABLE	EABL	AXLE	XLAE
ARMY	YMRA	AGED	DGAE
AWAY	AYWA	AIDE	DAIE
BACK	AKBC	ARID	IARD
BANK	NBKA	AXIS	XSAI
BIRD	RBDI	AVID	IVDA
BLOW	LWBO	BAIL	IABL
BLUE	ULBE	BEAK	EBKA
BODY	OYBD	BEVY	EYVB
BORN	ONRB	BLUR	URLB
BOTH	HOBT	BOAR	OABR
BURN	UBRN	BRAY	AYBR
BUSY	SYBU	CANE	EACN
CAMP	MPCA	CASK	SCKA
CENT	NCTE	CHAP	AHPC
CITY	TYCI	CHEF	EMCF
CLUB	BLCU	COIL	IOCL
COLD	OCLD	CRIB	IRCB
DARK	ADRK	DICE	EICD
DOWN	WDNO	DIRT	RTDI
DRAW	AWDR	DOVE	EDVO
DROP	PRDO	DRIP	IPDR
DUTY	UYDT	DUEL	LDEU
FACT	AFCT	DUPE	EDPU
FARM	AFRM	EDIT	IEDT

FAMILIAR WORDS	ANAGRAM	UNFAMILIAR WORDS	ANAGRAM
FAST	TFSA	ETCH	TCHE
FELT	LFTE	EMIT	IETM
FLOW	OWFL	SWAP	PSWA
FORM	OMRF	SWAB	AWSB
GIRL	RLGI	SURF	RFSU
GLAD	AGLD	FERN	RNFE
GOLD	LGDO	FEUD	UDFE
GREW	EWRG	FIST	STFI
HALF	AHLF	FLAP	AFPL
HAND	AHND	FOXY	YXFO
HANG	ANHG	FURL	RLFU
HARD	DRHA	GERM	RMGE
HELP	LPHE	GLIB	IBGL
HELD	EHLD	GLUE	UEGL
HOUR	URHO	GUST	STGU
HURT	RTHU	GRIT	IRTG
INCH	CHNI	GOSH	OHSG
JUST	STJU	HARP	RPHA
KIND	NDKI	HAUL	AUHL
LEFT	FLTE	HERB	EBHR
LONG	OGNL	HYMN	MNYH
LOST	OSTL	HURL	UHRL
MANY	ANYM	HIVE	VHEI
MARK	RMKA	ITCH	CTHI
MIND	NDMI	SUNK	USKN

FAMILIAR WORDS	ANAGRAM	UNFAMILIAR WORDS	ANAGRAM
MOST	STMO	SULK	KSLU
MUCH	CHMU	STUN	UTNS
NECK	CKNE	STAG	ATSG
NEWS	EWSN	STAB	ABST
NEXT	ENTX	JADE	EJDA
ONLY	OYNL	JERK	RKJE
PART	RTPA	JILT	LJTI
PICK	CKPI	JOWL	WLJO
PLAN	ANPL	JOLT	OJLT
PLAY	AYPL	JAIL	ILJA
REST	RSTE	JUNK	NKJU
RICH	RCHI	KILN	LNKI
ROCK	OKCR	KITE	IKTE
SALT	SLTA	KNOB	OBNK
SEND	NDSE	SNIP	IPSN
SHIP	IPSH	LUSH	SHLU
SHOT	OTHS	LARD	ALRD
SHOW	WOHS	LEWD	ELWD
SICK	KCSI	LICK	CKLI
SNOW	OWSN	LIMP	MPLI
SOFT	OSTF	LURK	RKLU
SOLD	DSLO	LYRE	YRLE
SONG	NGSO	MALT	ALMT
SORT	RTSO	MINT	NTMI
STAY	AYST	MINK	NKMI

FAMILIAR WORDS	ANAGRAM	UNFAMILIAR WORDS	ANAGRAM
STOP	OPST	MORN	RNMO
SUCH	CHSU	MOTH	OMHT
TALK	LTKA	MYTH	YMHT
THAN	ANHT	NEWT	WNTE
THEY	HTEY	NICK	NKCI
THIN	HNTI	NOUN	ONUN
TRIP	IRPT	UNDE	NEDU
TURN	RNTU	NUMB	UMBN
TYPE	YPTE	SMUT	UMST
UPON	OPNU	SLUR	URSL
VERY	RYVE	ORGY	RGYO
WALK	LKWA	OVAL	AOVL
WANT	ANTW	OATH	HTAO
WARM	AMRW	OGRE	OEGR
WASH	AHSW	SLIT	ILTS
WEST	SWTE	SLAB	ABSL
WHOM	OMWH	PAWN	WNPA
WILD	LDWI	PECK	CKPE
WIND	NDWI	PELT	LTPE
WING	NGWI	PERK	RKPE
WISH	HSWI	PINT	NTPI
WORD	RDWO	PORK	RKPO
WORK	RKOW	SKID	IDSK
YARD	RDYA	SIFT	FTSI
BEST	STBE	SLAT	ATSL

FAMILIAR WORDS	ANAGRAM	UNFAMILIAR WORDS	ANAGRAM
COST	CTSO	SLAM	AMSL
FIND	NDFI	SLAG	AGSL
FISH	SHFI	SKIP	IPSK
HOLD	LDHO	RAFT	FTRA
LAST	SLTA	RAKE	AEKR
MUST	UTSM	RASH	ASRH
PAST	TSPA	RASP	PSRA
POST	PTOS	RELY	YLRE
RING	NGRI	ROUT	UOTR
SHOP	PSHO	SCAB	ASBC
SIGN	GNSI	SCAN	ACSN
SING	NGSI	SERF	RFSE
SKIN	NSIK	SHOD	OHSD
SPOT	OTSP	SHUN	UHNS
STEP	EPST	SIFT	FTSI
THEM	EMHT	SILT	TLSI
THEN	HNTE	TAXI	XTAI
THIS	IHST	TEXT	TXTE
TOLD	OTDL	THAW	AWHT
WENT	NTWE	TIDY	IYDT
WHAT	HWTA	TRAY	RYTA
WITH	IWHT	TREK	ETKR
CAME	ACEM	TURF	RFTU
COAL	OALC	TUSK	UKST
EACH	EHAC	TWIG	WGTI

AD-A063 505 VIRGINIA POLYTECHNIC INST AND STATE UNIV BLACKSBURG --ETC F/G 5/8
INFORMATION TRANSFER FROM COMPUTER-GENERATED DOT-MATRIX DISPLAY--ETC(U)
OCT 78 H L SNYDER, M E MADDOX DAHC04-74-G-0200
UNCLASSIFIED HFL-78-3/ARO-78-1 ARO-12355.7-EL NL

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FAMILIAR WORDS	ANAGRAM	UNFAMILIAR WORDS	ANAGRAM
EASY	AESY	TUCK	CTKU
FAIR	IRFA	VENT	NVTE
FIVE	VFEI	VERB	RBVE
GAME	EMGA	VEST	ETSV
KNEW	WKNE	WARP	RPWA
LAID	IADL	WELD	LDWE
LAND	NDLA	WHIM	IMWH
LIKE	IKLE	WINK	NKWI
MINE	IMNE	WISP	IWSP
ONCE	OENC	WREN	ENRW
PAGE	EAGP	YARN	RNYA
PATH	HTPA	YELP	LPYE
RULE	EULR	ZEST	TZSE
SENT	ESTN	*FLUX*	*UXLF*
SIZE	EISZ	BULB	BLBU
TRUE	UETR	MENU	ENMU
VIEW	EWVI	TROD	ODTR
YOUR	UOYR	TSAR	RSTA
SURE	RSEU	FANG	NGFA

APPENDIX C

REGRESSION PROGRAM OUTPUT

TINKER TASK REGRESSION

STEPWISE REGRESSION PROCEDURE FOR DEPENDENT VARIABLE TIME

VARIABLE HMTFA ENTERED $R^2 = 0.573$

	DF	SUM OF SQUARES	F	PROB > F
REGRESSION	4	25.78730404	16.47	0.0001
ERROR	49	19.18147827		
TOTAL	53	44.96878231		

	B VALUE	STD ERROR	F	PROB > F
INTERCEPT	1.42974564			
VSQR	0.02309011	0.00336082	47.20	0.0001
HMTFA	0.36381271	0.14106783	6.65	0.0130
VMTFA	0.22109696	0.06255004	12.49	0.0009
HMLOG	-4.82512890	0.96210803	25.15	0.0001

Note: All variables in the model are significant at the 0.1000 level.

RANDOM SEARCH REGRESSION

MINIMUM R^2 IMPROVEMENT FOR DEPENDENT VARIABLE TIME

VIDV REPLACED BY HDIV $R^2 = 0.498$

	DF	SUM OF SQUARES	F	PROB > F
REGRESSION	6	71.12068210	7.80	0.0001
ERROR	47	71.47033540		
TOTAL	53	142.59101750		

	B VALUE	STD ERROR	F	PROB > F
INTERCEPT	-48.50317655			
HFLOG	-138.48583533	42.00590217	10.87	0.0019
VFLOG	192.89327525	55.15904890	12.23	0.0010
HMTFA	-0.64218638	0.11532174	31.01	0.0001
HSQR	-0.73397975	0.19628144	13.98	0.0005
VSQR	0.98240802	0.25813230	14.48	0.0004
HDIV	-0.04311609	0.00812896	28.13	0.0001

Note: The above model is the best six-variable model found.

MENU SEARCH REGRESSION

STEPWISE REGRESSION PROCEDURE FOR DEPENDENT VARIABLE TIME

VARIABLE HDIV REMOVED $R^2 = 0.471$

	DF	SUM OF SQUARES	F	PROB > F
REGRESSION	3	13.22253643	14.86	0.0001
ERROR	50	14.82603861		
TOTAL	53	28.04857504		

	B VALUE	STD ERROR	F	PROB > F
INTERCEPT	0.78045593			
VSQR	0.02433814	0.00484864	25.20	0.0001
HLOG	2.71984434	0.41429738	43.10	0.0001
VMFTA	0.19311360	0.04716379	16.77	0.0002

Note: All variables in the model are significant at the 0.1000 level.